The High Field Compact Mirror Path to Fusion Energy

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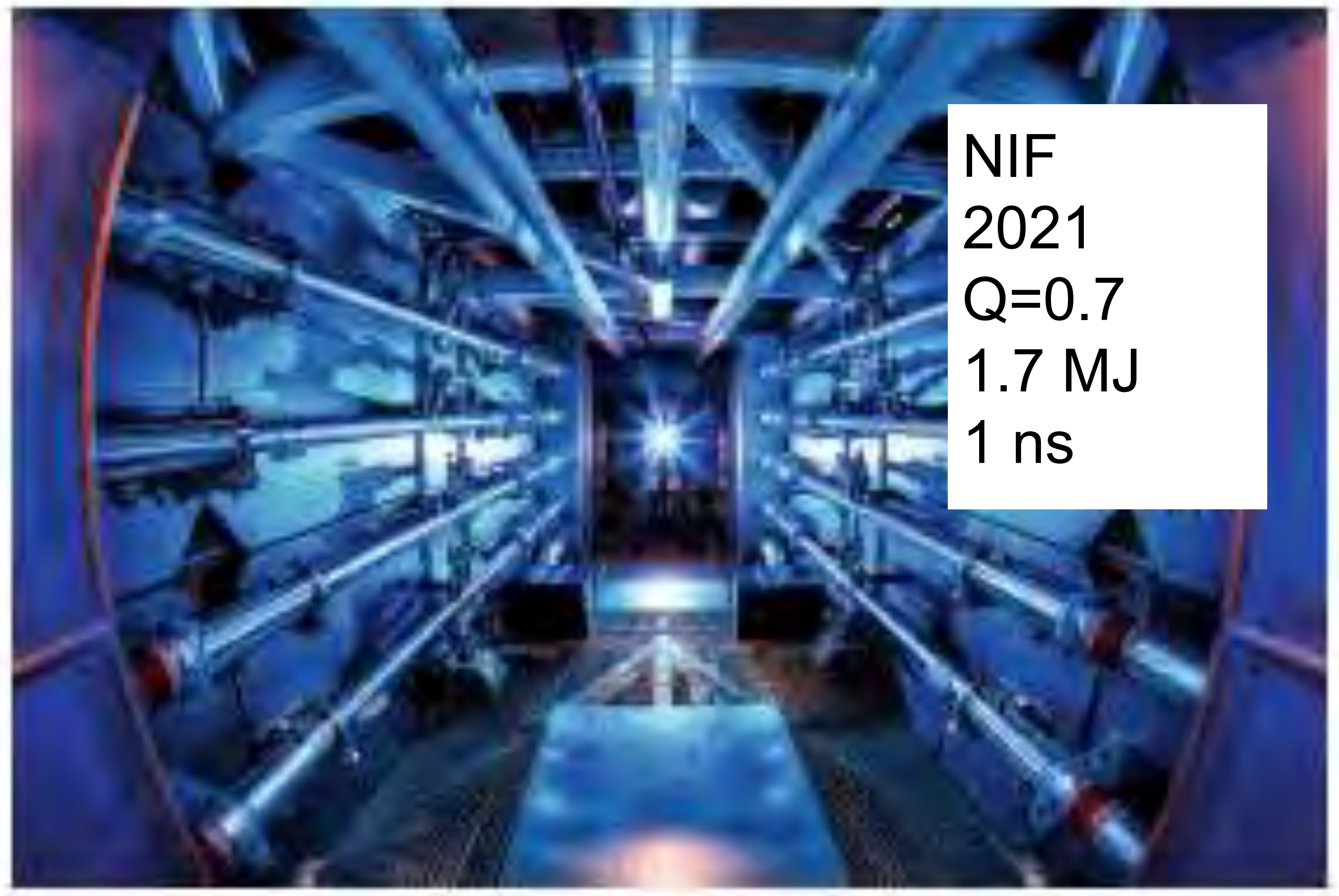
50+ years of research has us at the cusp of using fusion energy from deuterium and tritium

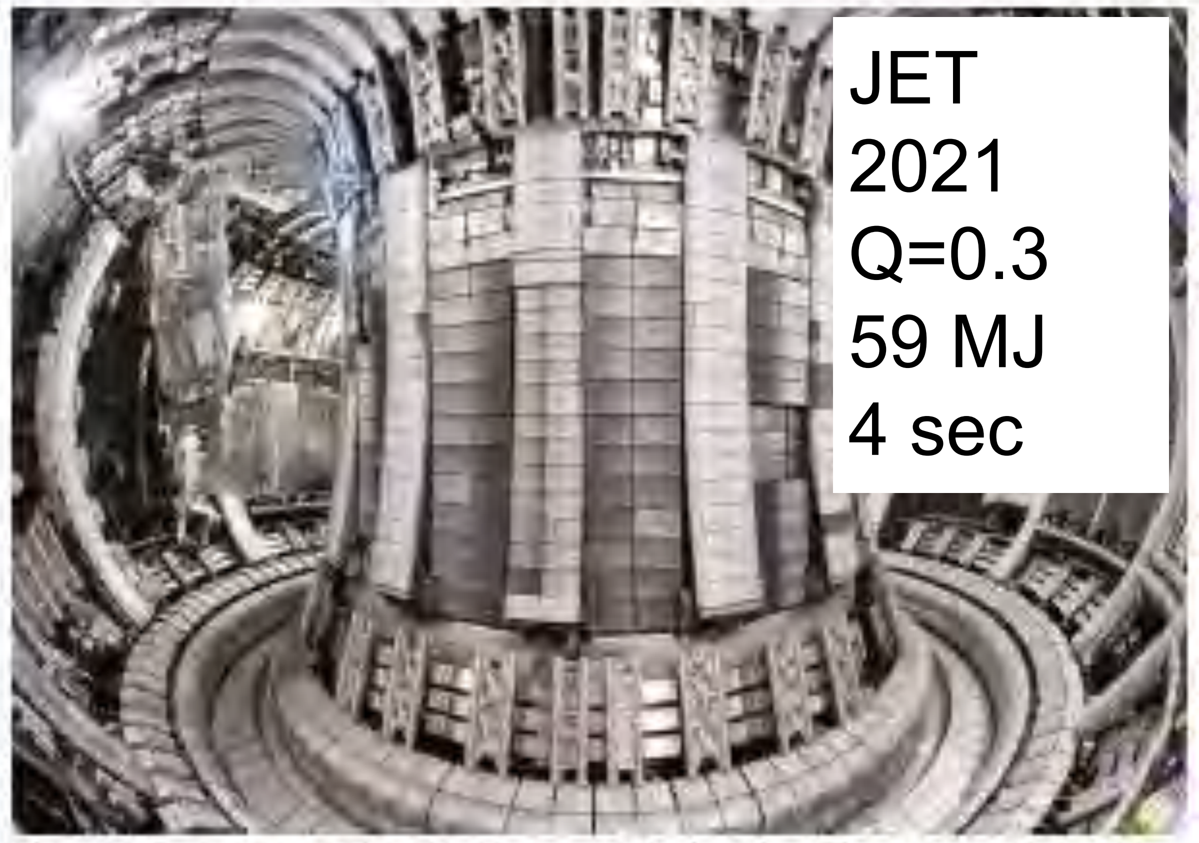
Fusion news ignites optimism

News of a 1.3-MJ-output-energy experiment at the National Ignition Facility in the United States in August has
raised hopes that laser-based fusion is back on track.



Credit: Damien Jamison / Lawrence Livermore National Laboratory

Nature PhotoNics | VOL 15 | OCtOber 2021 | 713 | www.nature.com/naturephotonics



The Joint European Torus tokamak reactor near Oxford, UK, hosted experiments with tritium.

NUCLEAR-FUSION REACTOR SMASHES ENERGY RECORD

The Joint European Torus has doubled the record for the amount of energy made from fusing atoms.

Phoenix and SHINE Achieve New World Record for Strongest Nuclear Fusion Reaction in a Steady-State System

October 02, 2019 08:00 ET | Source: Phoenix; SHINE Medical Technologies LLC

- During the next decade we will see at least two experiments demonstrate viability of the tokamak
  - Iter, dt planned for 2035, 500 MW_t for 1000 sec, Q~10
  - SPARC, DT planned for 2027, Q~10

- Appetite in the private sector is growing
  - > $4B investement by venture capital in past few years
  - CFS likely leading the US Pilot Plant Race with ARC

The Problem

The vision for fusion power plants based on stellarators and tokamaks are enormous, capital intensive, and complex

- difficult to fund
- long and risky construction projects
- unreliable

$22B, first conceived 1992, dt operation 2035

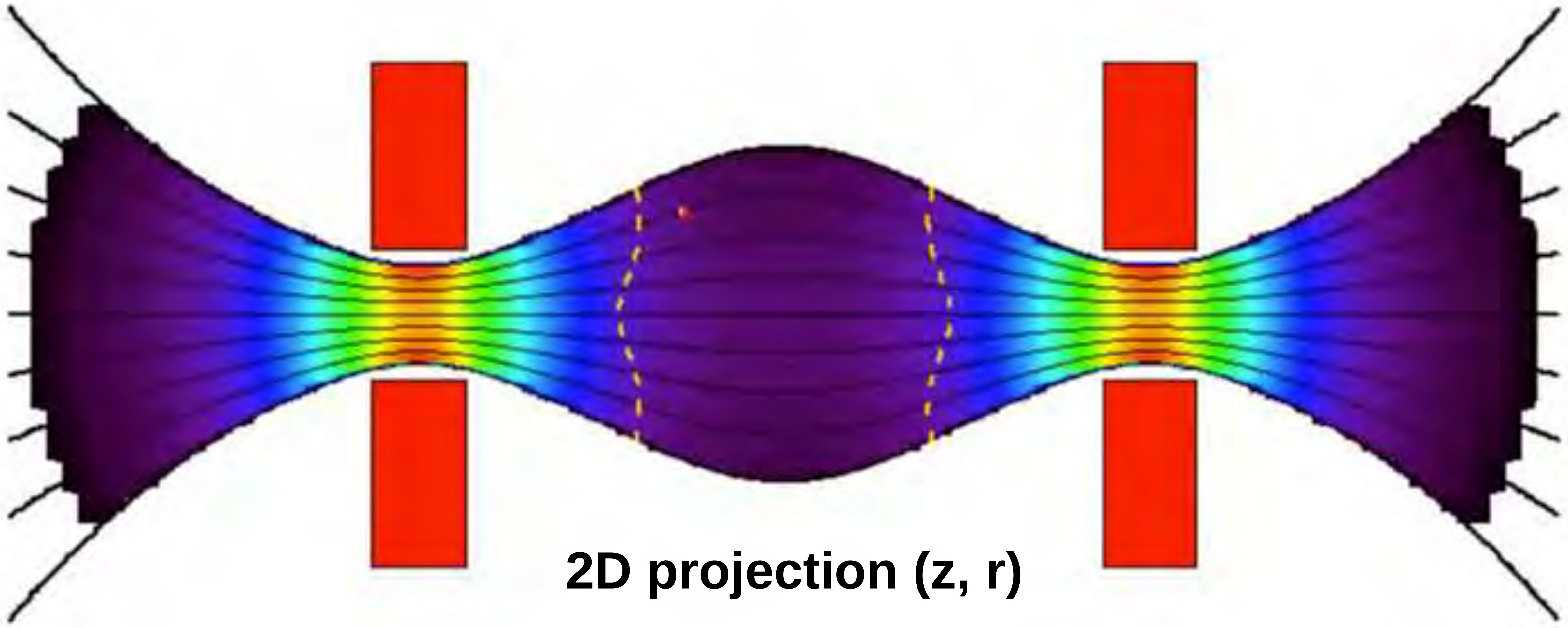
Wendelstein 7X
conceived 1992
First plasma 2015
cost > 1B Euros

Its not just Iter:
also W7-X, NCSX, NSTX-U…

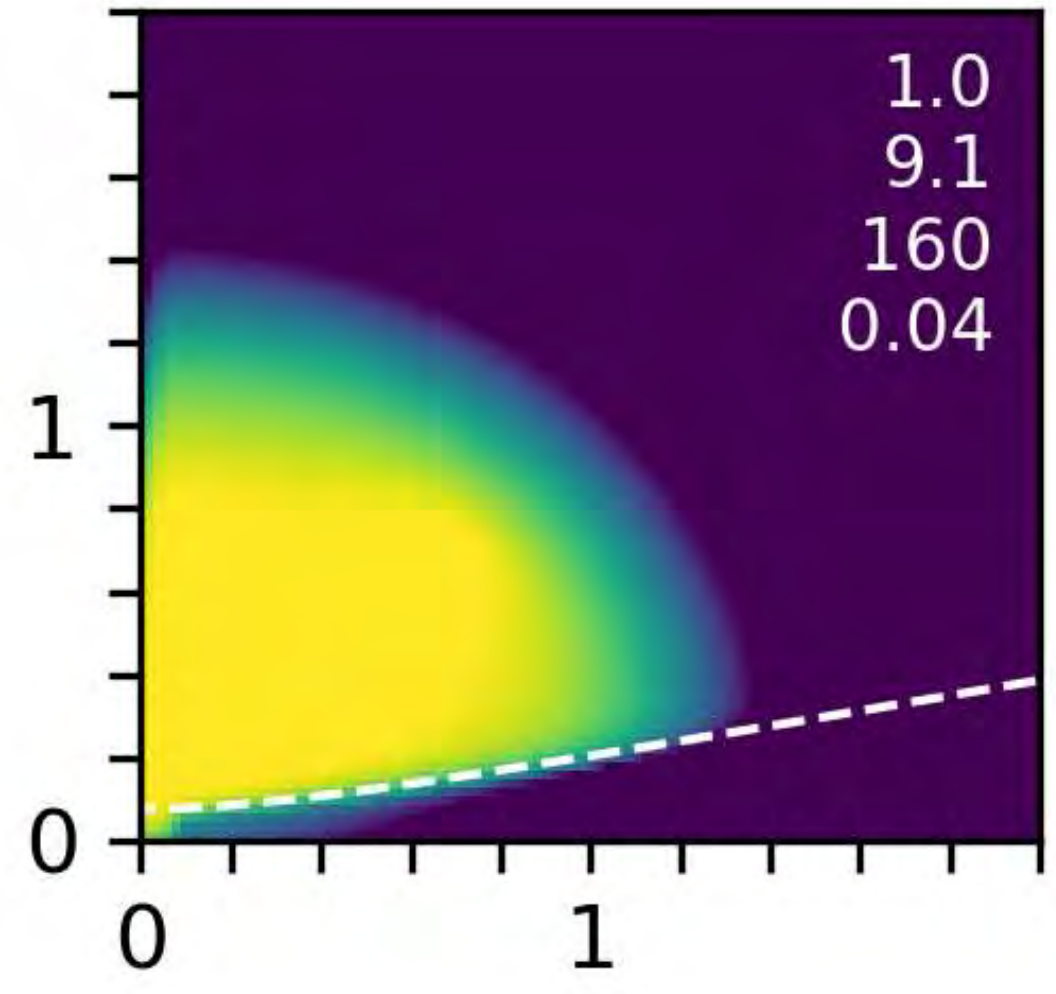
The Solution (one person’s opinion)

Simplify and innovate, embrace risk as a necessity, to make fusion more compact and dependable

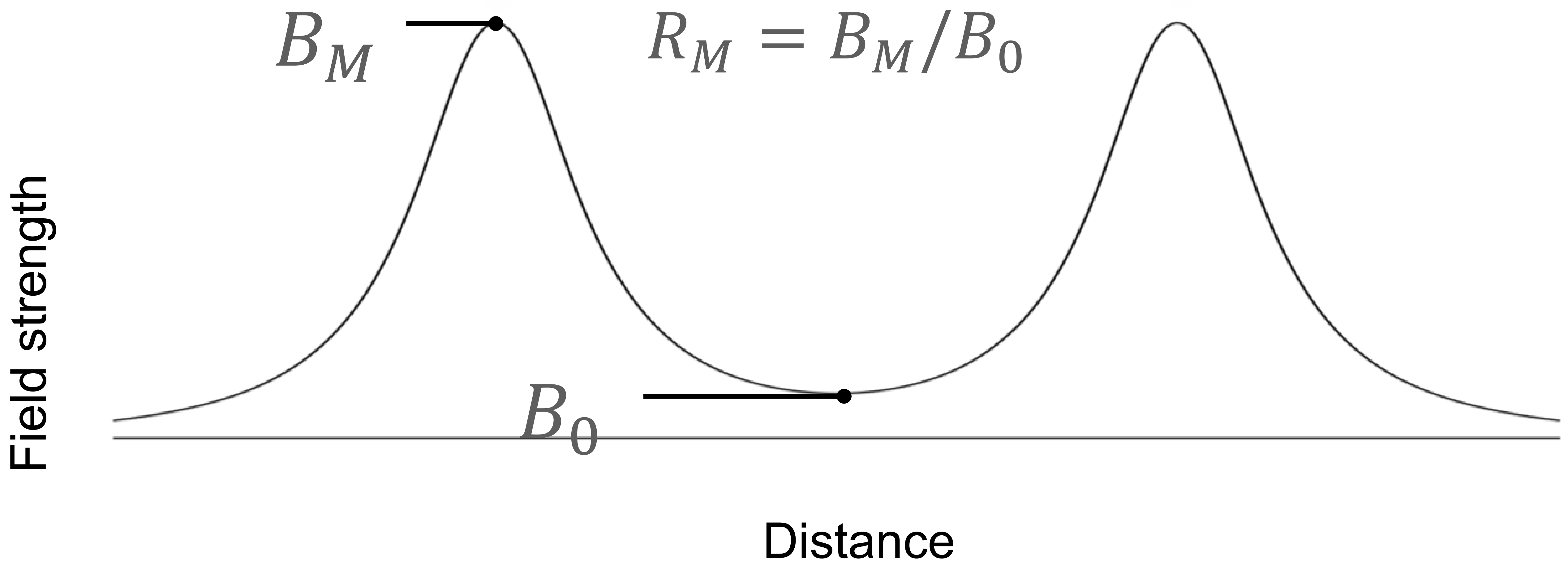
Simplest confinement is the magnetic mirror



2D projection (z, r)



$$\sin\theta = \frac{1}{\sqrt{R_M}}$$



- **Theoretical confinement time from angular scattering of fast ions into loss cone:**

$$\tau_p = 0.00028\,\frac{E_{b,keV}^{3/2}}{n_{20}}\log_{10}R_M\,sec$$

- Electrons confined by ambipolar potential

$$e\phi \sim 5 - 7kT_e$$

Breakeven in a larger mirror-ratio beam-heated weakly-collisional mirror

- Well verified and validated theory shows

$$\tau_p = 0.00028 \frac{E_{b,keV}^{3/2}}{n_{20}} \log_{10} R_M \, sec$$

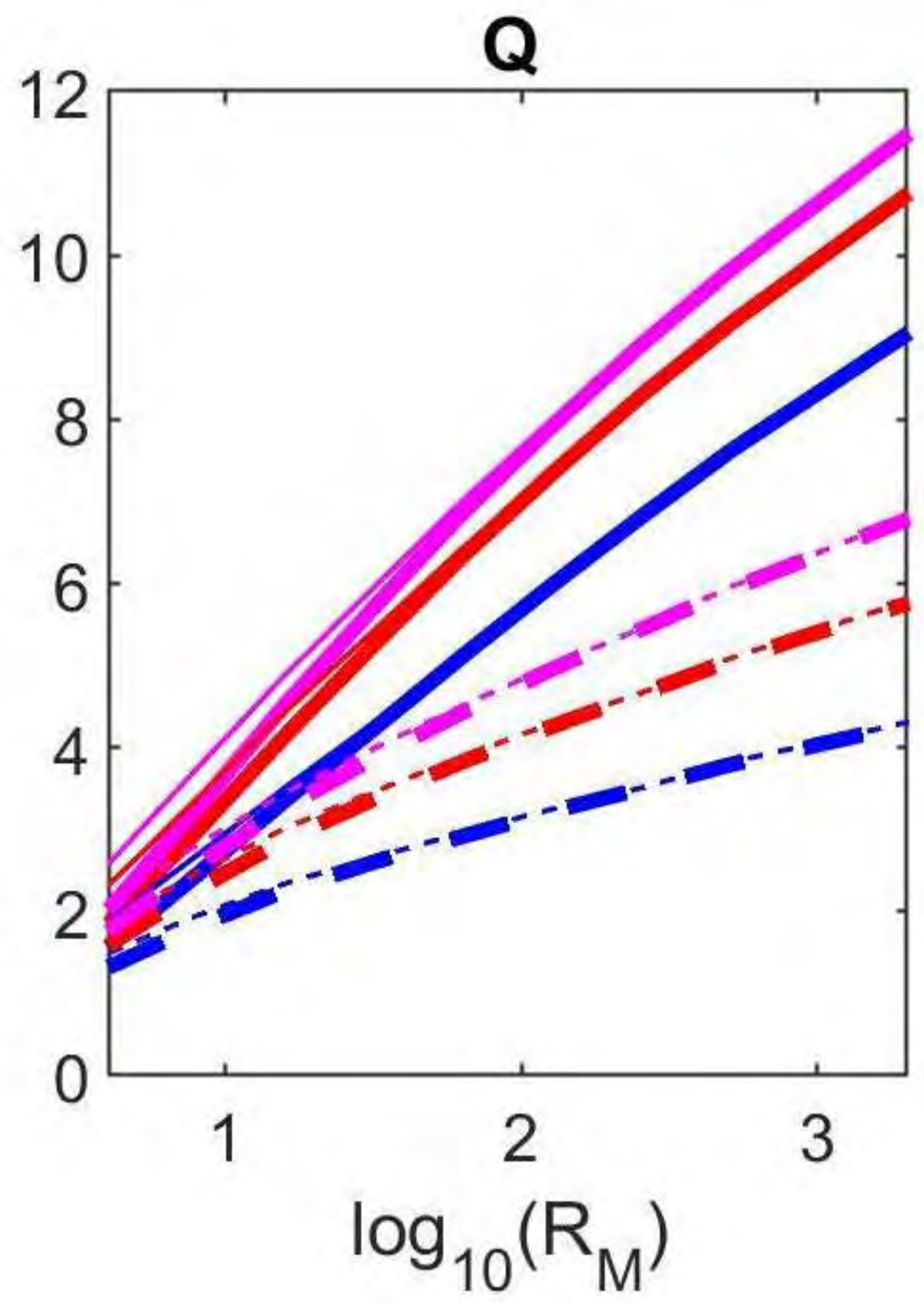
- Q optimizes around $E_b \sim 150\, keV$

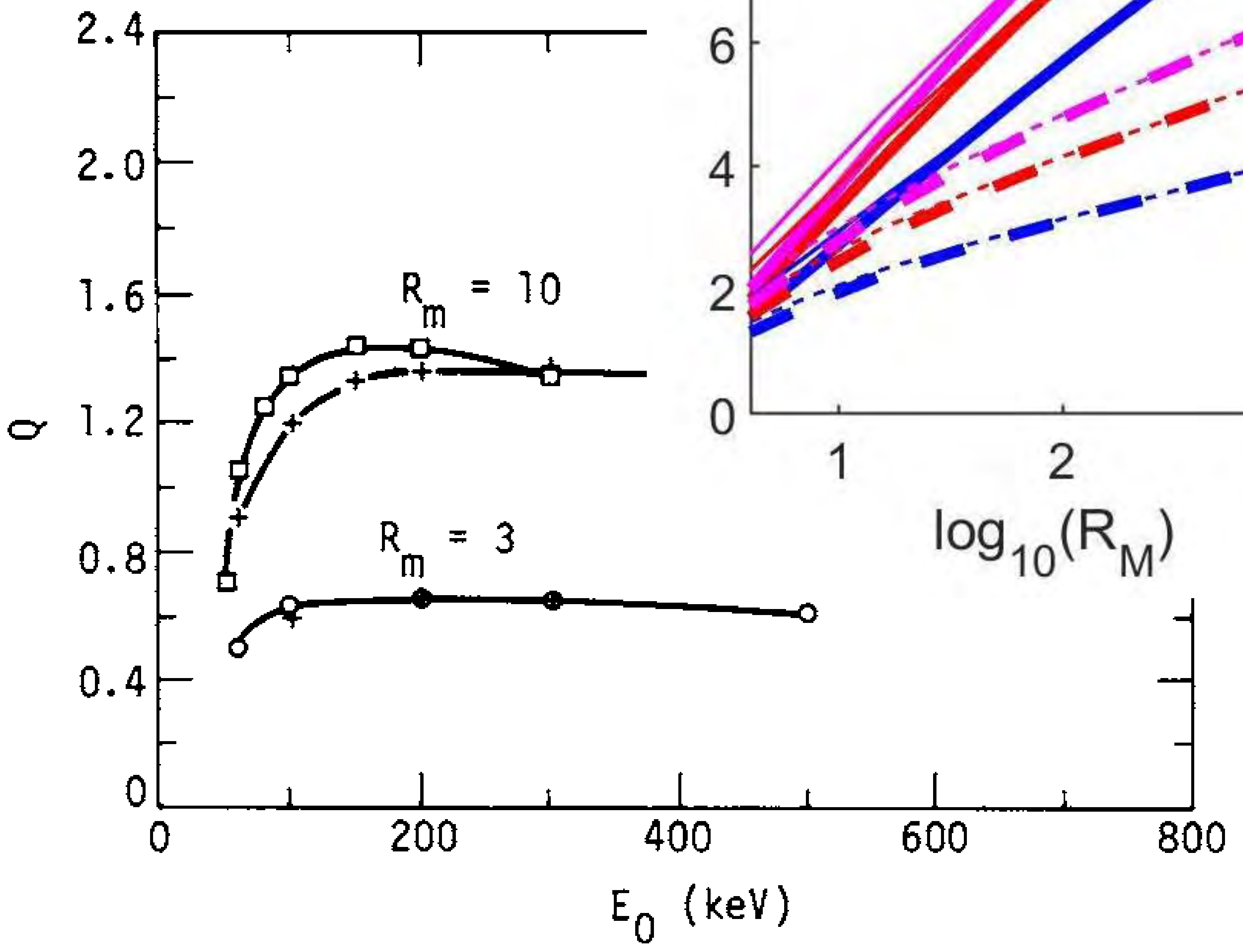
$$P_{nbi} = I_b E_b = \frac{enV}{\tau_P} E_b \sim \frac{10^{20}}{3} \frac{n_{20}^2}{E_{b,100keV}^{1/2} \log_{10} R_M} V \frac{MeV}{sec}$$

$$P_{fus} = \frac{1}{4} \langle \sigma v \rangle n^2 \mathcal{E}_{fusion} V \sim 5 \times 10^{19} n_{20}^2 V \frac{MeV}{sec} \; for \mathcal{E}_{fusion} = 22.4\, MeV \, and T_i \sim 100\, keV$$

- Independent of plasma parameters, size or B

$$Q \equiv \frac{P_{fusion}}{P_{nbi}} \propto \langle \sigma v \rangle E_b^{1/2} \log_{10} R_M \sim 1.5 E_{b,100keV}^{1/2} \log_{10} R_M$$



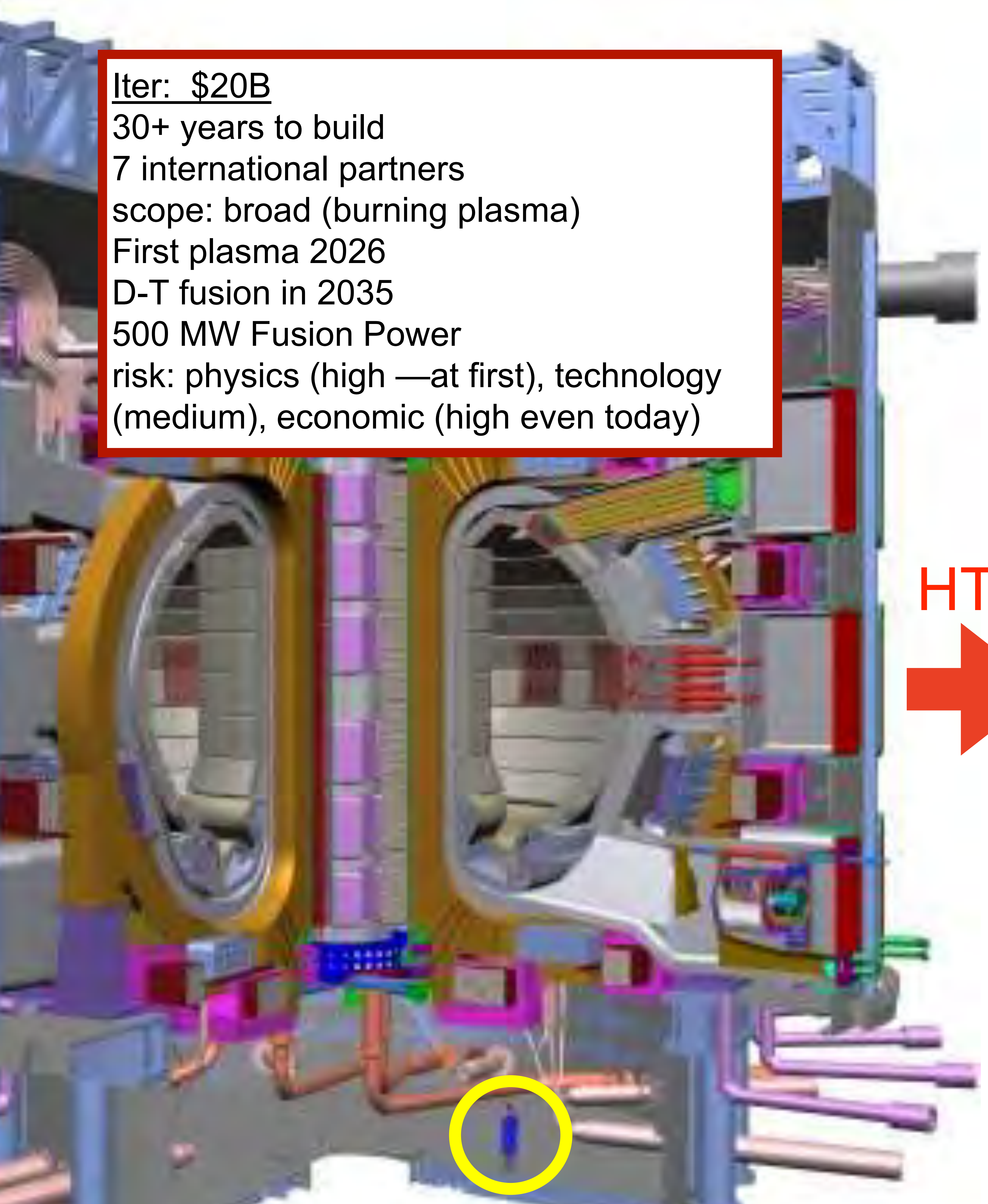


COMPARISON OF Q VALUES ($R_m = 10$)

Code description	Plasma species			
	D-e-T	D-e-T-α	D-e-³He	D-e-³He-α-p
One-dimensional code; P_0 only	1.22	1.39	0.244	0.264
One-dimensional code; P_0 and P_2	1.44	1.68	0.289	0.312
Two-dimensional code; normal mode source	1.38	1.61	0.278	0.301
Two-dimensional code; narrow source	1.71	1.99	0.337	0.365

KILLEEN, J., MIRIN, A. A. & RENSINK, M. E. The Solution of the Kinetic Equations for a Multispecies Plasma *Methods Comput Phys Adv Res Appl* **16**, 389–431 (1976).

conjecture: reducing size and simplifying will make fusion more viable

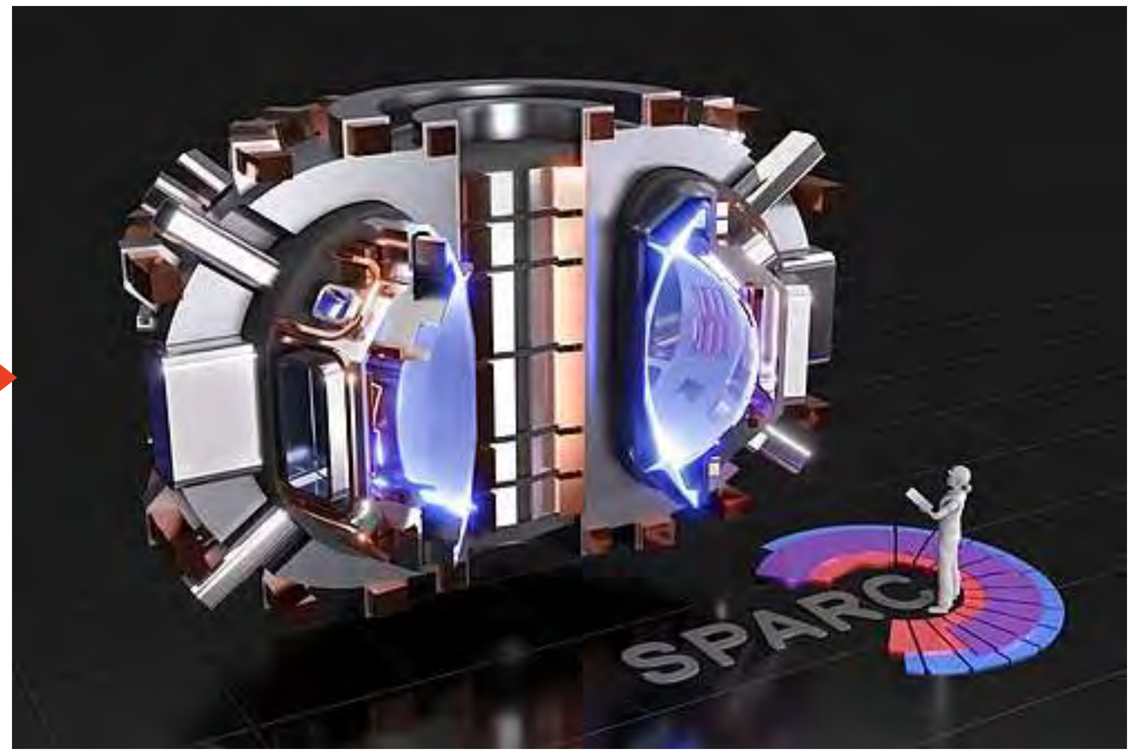


Iter: $20B
30+ years to build
7 international partners
scope: broad (burning plasma)
First plasma 2026
D-T fusion in 2035
500 MW Fusion Power
risk: physics (high —at first), technology (medium), economic (high even today)

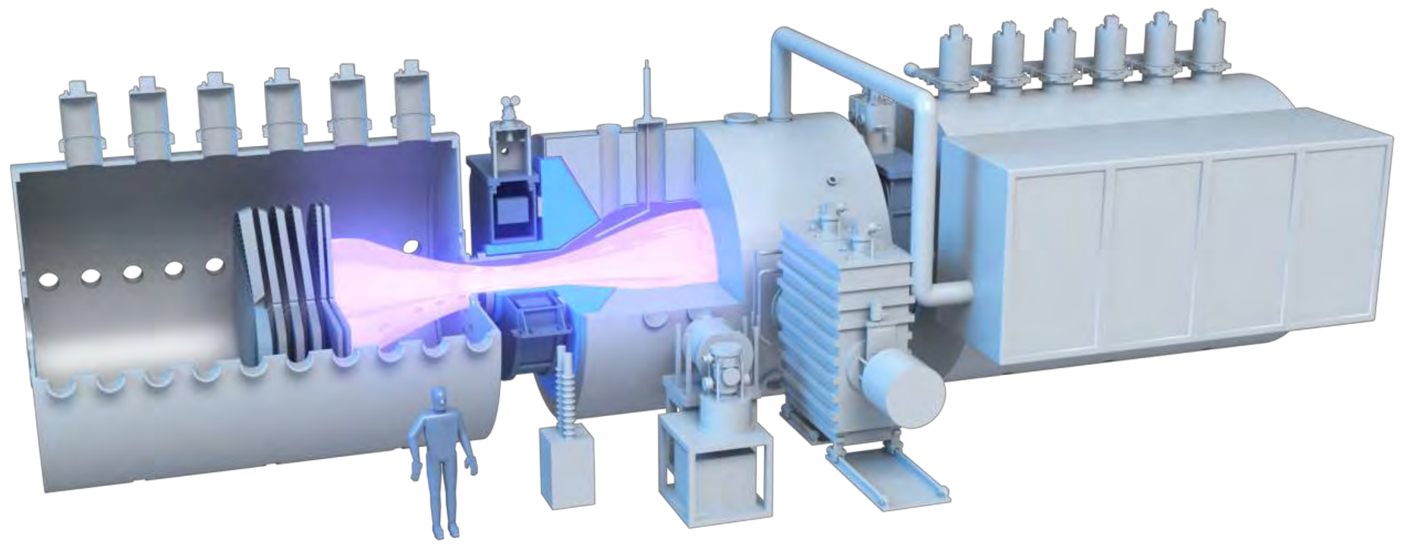
↑
Person!

Sparc: $2B
5 years to build
one company
$Q_{scientific}$>1 limited scope
First plasma 2025
140 MW fusion power
risk: physics (low), technology (high), economic (medium)

HTS



WHAM++: $200M (??)
5 years to build
one company
$Q_{electric}$>1 limited scope
First plasma 2027
5 MW fusion power
risk: physics (high for integration), technology (medium), economic (low—by fusion standards)



simpler and less costly Q>1 demonstration will translate to a more economical and reliable pilot plant

Path to Commercial Scale

2020 | 2024 | 2028 | 2032 | 2036

WHAM 1.0

WHAM++ Q_{equiv}~1 (dd) short pulse

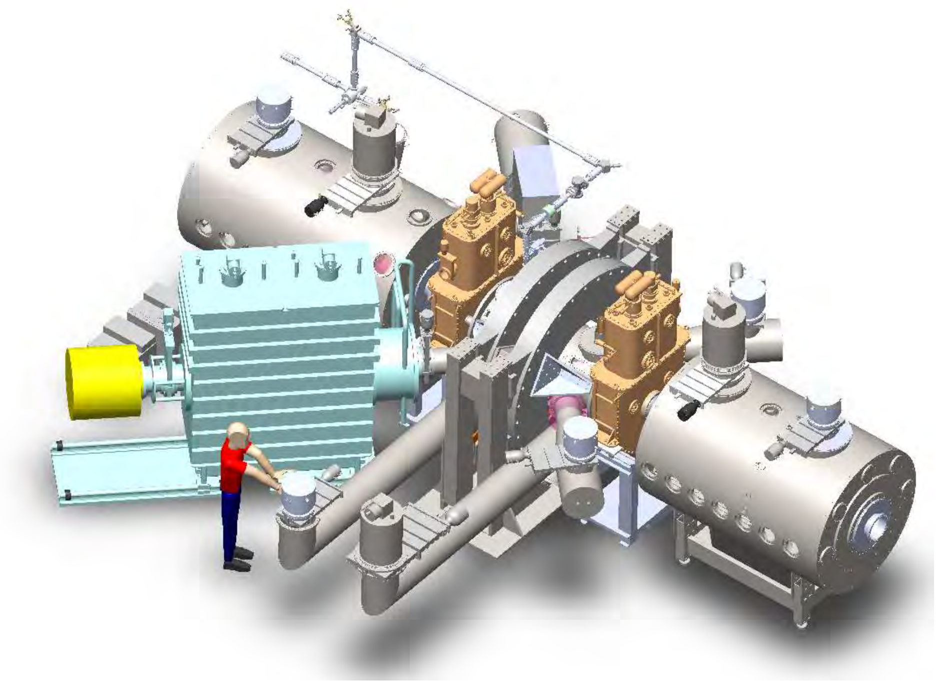
WHAM++ Q~1 (dt) steady-state

WHAM++ high B_p (go/no go)

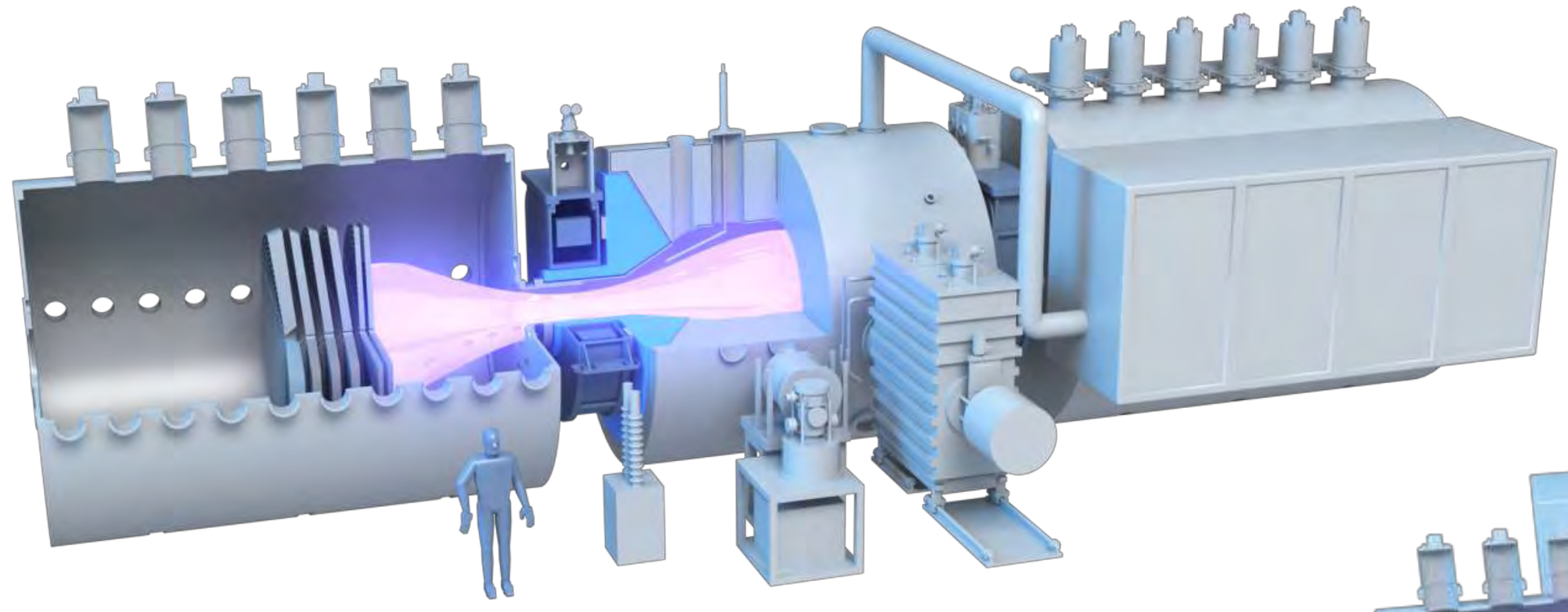
HAMMir (2 x WHAM++, central cell)

Industrial Heat & Power

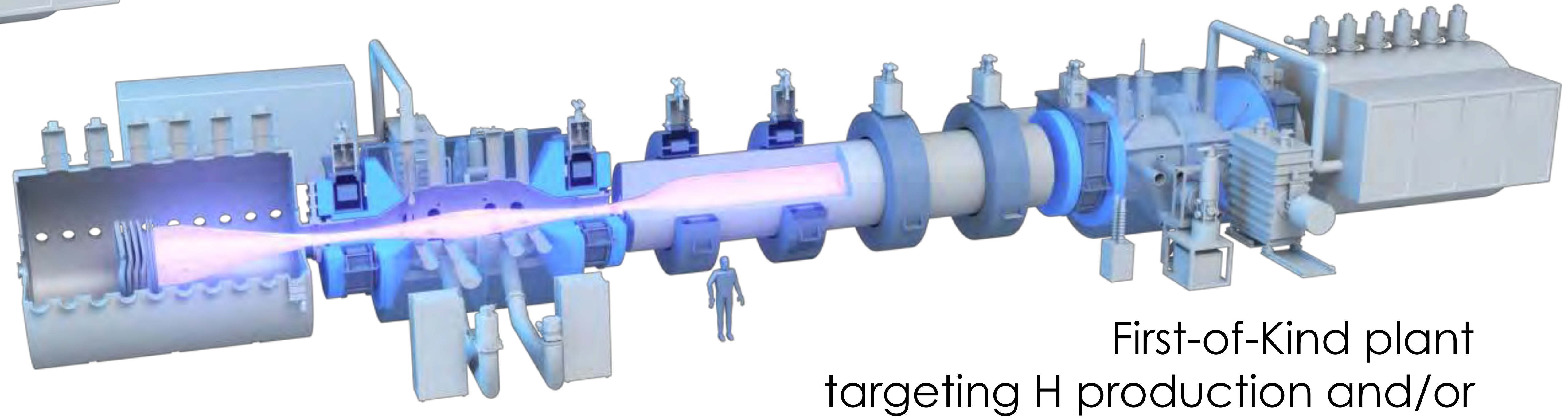
Initial independent estimated cost of thermal energy <$7/mmBtu



- HTS
- MHD, Confinement
- rf ion acceleration



- Integrated physics, PFCs
- component and materials testing
- DT fuel cycle demonstration, 10^{18} n/s
- Q_{elec}~1 in steady-state



First-of-Kind plant
targeting H production and/or
process heat with industrial partner
Q>10 ca. 300 MW_t

Attractive Features of Axisymmetric Mirror

1. Simple cylindrical geometry for construction and iterability
   - high-field, insulator free planar coils, lower tech central cell magnets
   - Linear geometry attractive for R*eliability*, A*vailability*, M*aintainability*, I*nspectability*
2. Simple high temperature blanket geometry
3. direct energy conversion of plasma losses into DC power
4. no minimum power
   - extensible in length to control output power output
   - Q~1 milestone can be met with a bitesize chunk
5. Intrinsically steady-state, no plasma current and no disruptions
6. The obvious geometry for a fusion powered rocket engine…but also a good form factor for industrial process heat
7. Development path provides low-tritium-use materials testing, component testing, fuel cycle demonstration platform
8. Physics is mature (leading alternate to the tokamak), but program in 1985 was ahead of its time relative to technology

What could possibly go wrong?

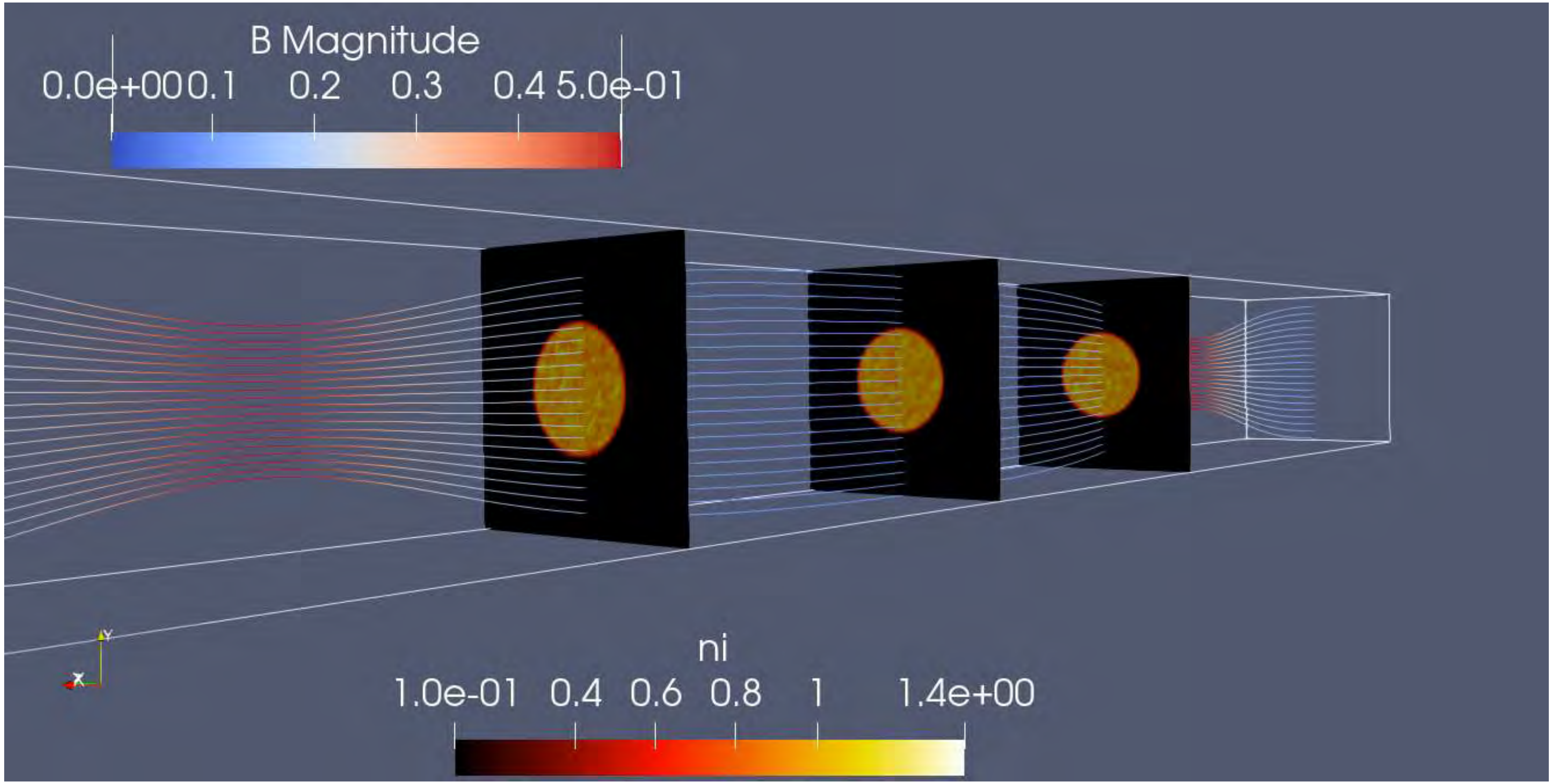
and

Hasn’t this been tried before?

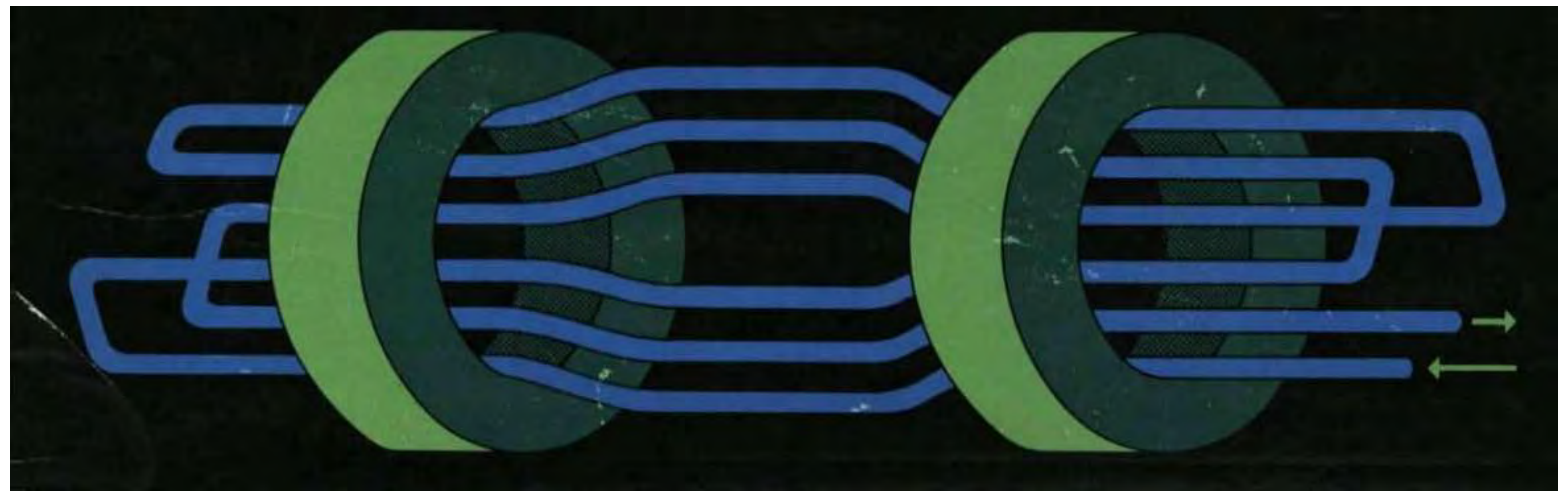
Hint: MHD and Kinetic Instability

So what could go wrong?

Instability in a 3D Hybrid simulation using VPIC: Plasma science and computation has now advanced so far that we can simulate almost anything before building it



Minimum-B MHD stable configurations



- Ioffe bars. (Kurchatov Institute)

- Baseball coil. (Culham, LLNL)

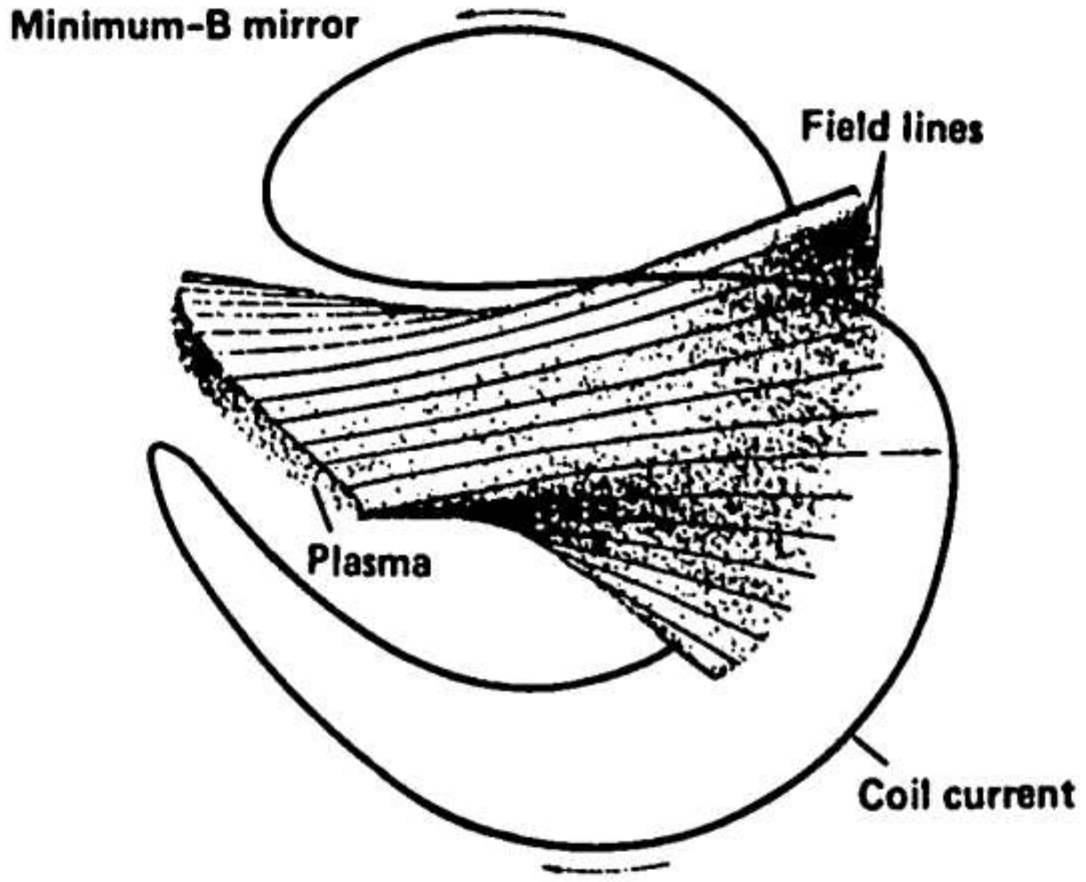
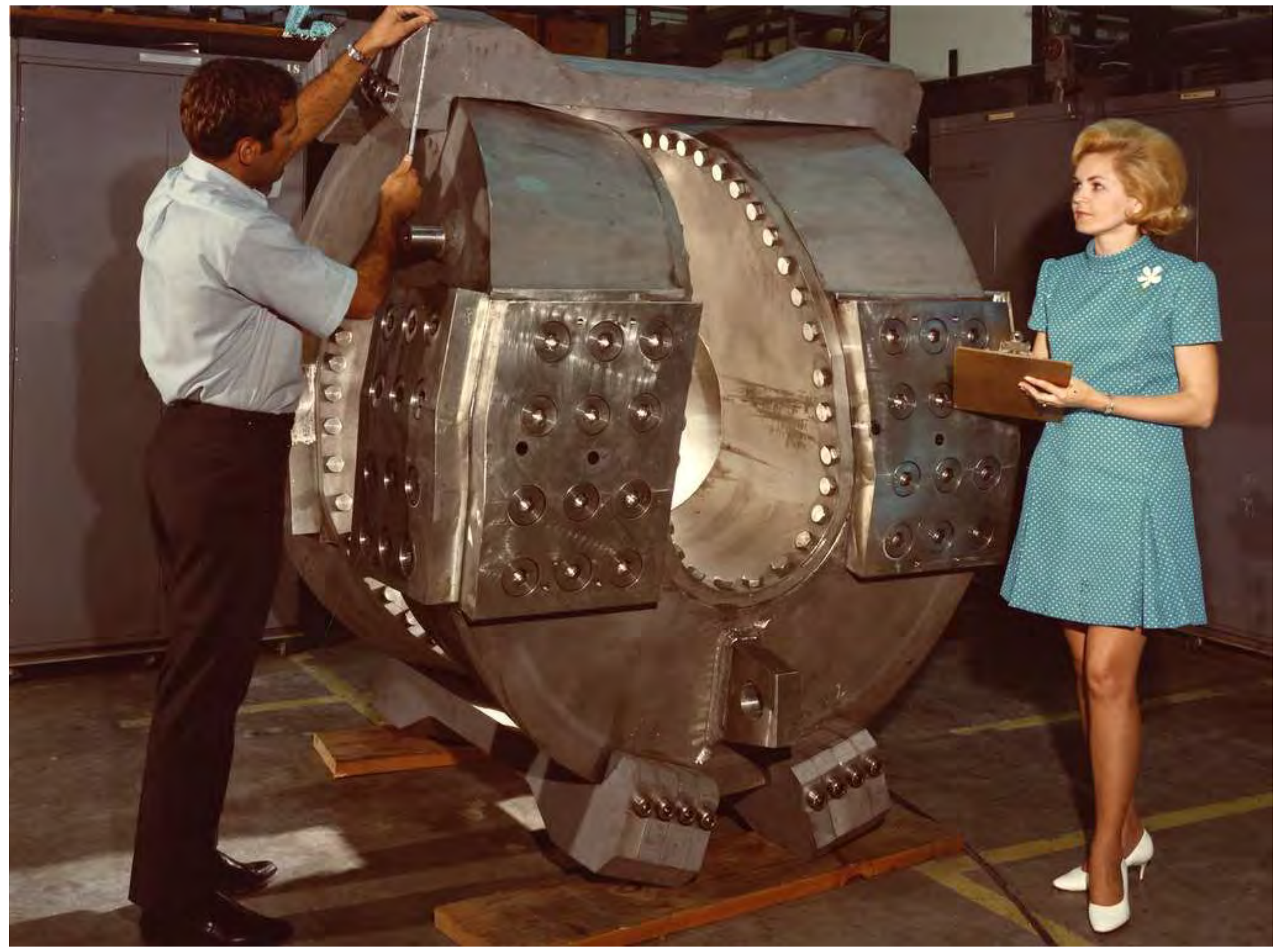


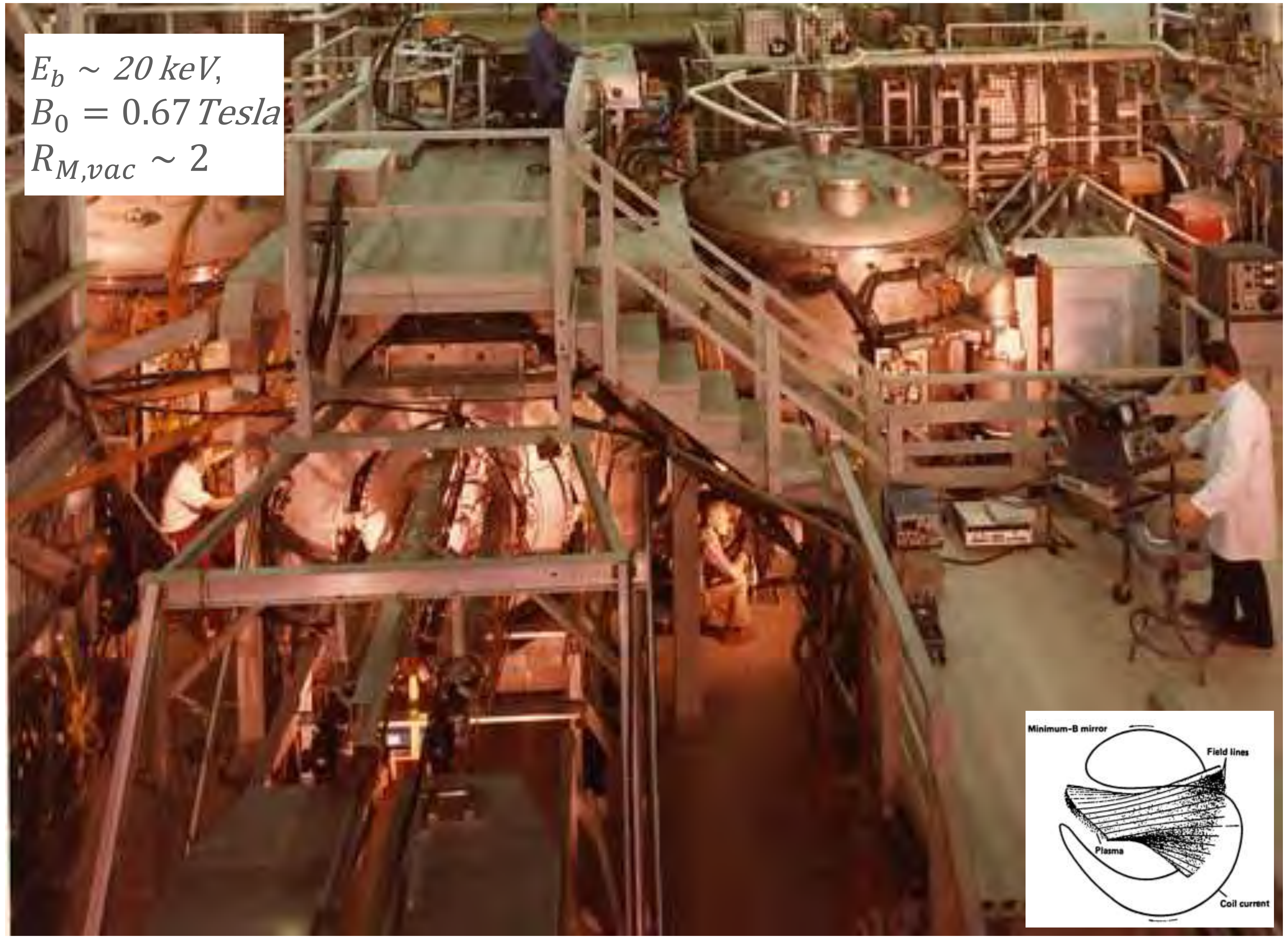
FIG. 1. Schematic representation of the coil and field lines in a magnetic-well field as produced by a "Baseball" coil.



- Ying-Yang coils. (LLNL)

Non-circular coils successful in stabilizing the plasma;
Major downsides are decreased particle confinement, simplicity and field strength/mirror ratio.

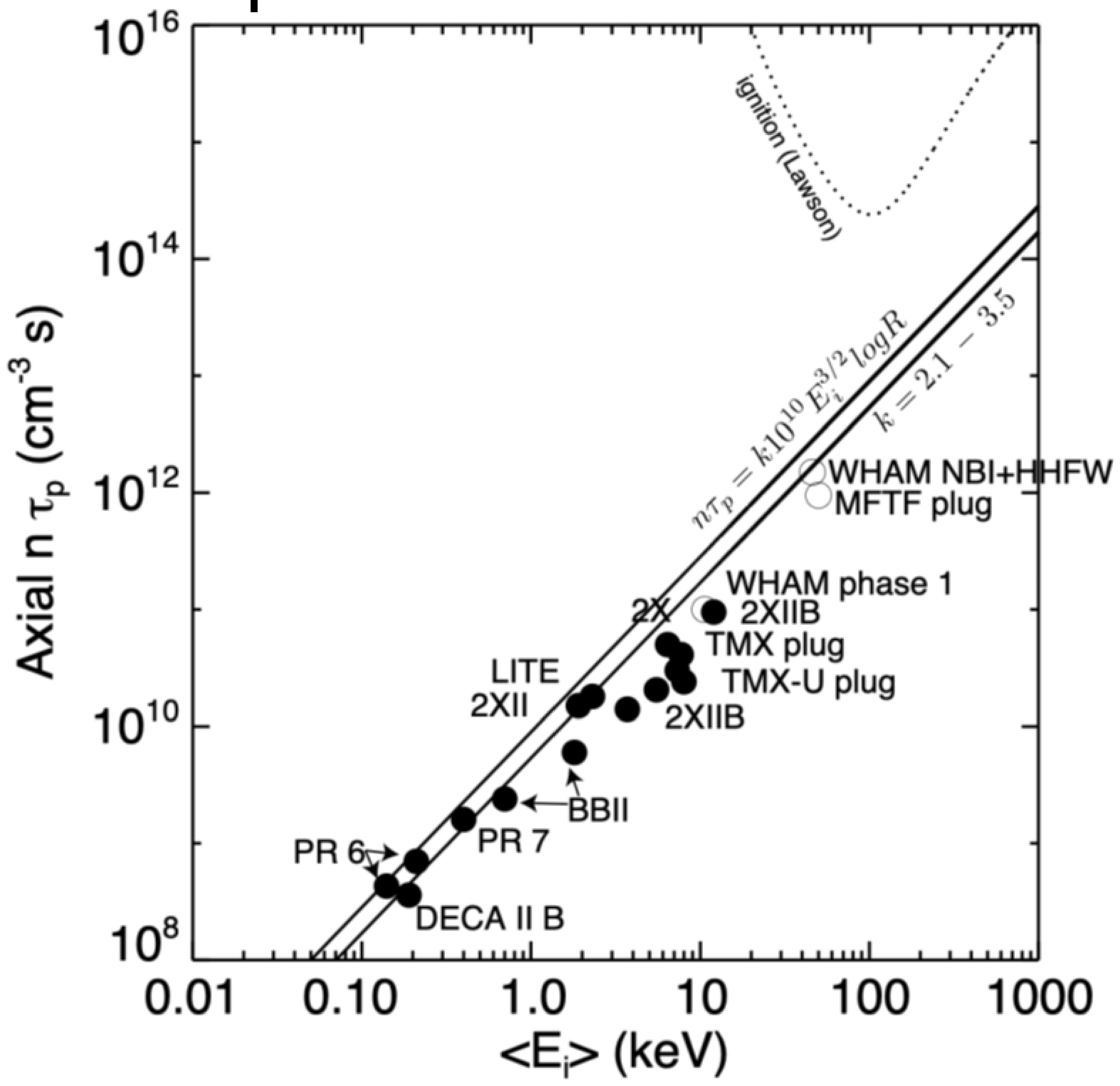
2XIIB showed near classical scaling of confinement and $\beta \sim 1$



- Mirrors want to run at high ion energy

$$\tau \sim E_b^{3/2} \ln R_M / n$$

- Kinetic Instability stabilized by plasma guns at ends filling ambipolar hole
  - later on TMX with skewed NBI injection to trap warm plasma



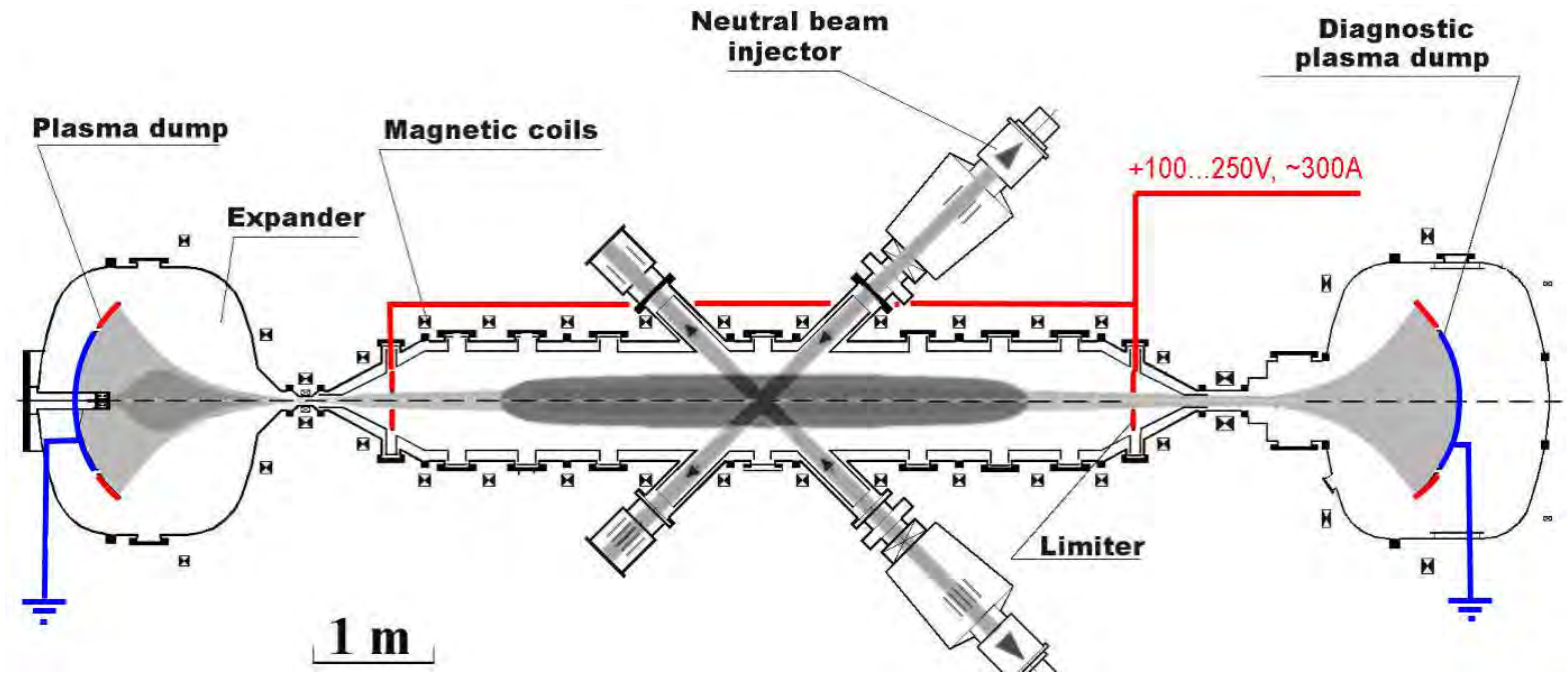
In retrospect: skewed injection, E_b=100 keV, and high beta $R_M = R_{M,vac}/\sqrt{1-\beta}$ would have been close to Q~1 with optimistic assumptions

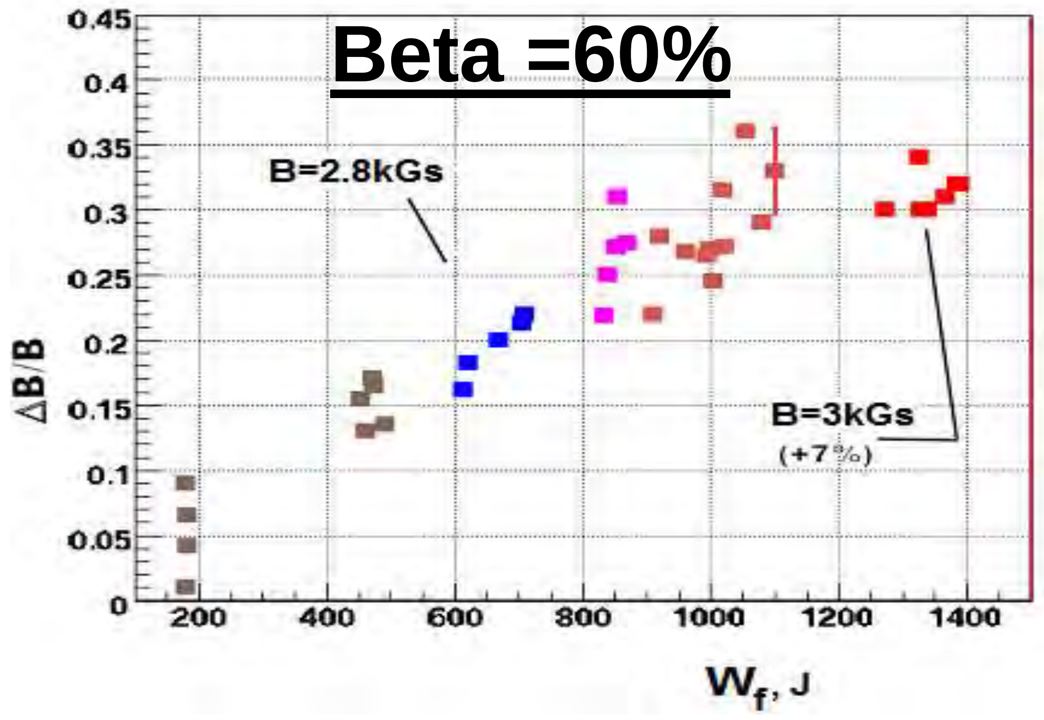
F. H. Coensgen, W. F. Cummins, B. G. Logan, A. W. Molvik, W. E. Nexsen, T. C. Simonen, B. W. Stallard, and W. C. Turner, *Stabilization of a Neutral-Beam—Sustained, Mirror-Confined Plasma*, Phys Rev Lett **35**, 1501 (1975).

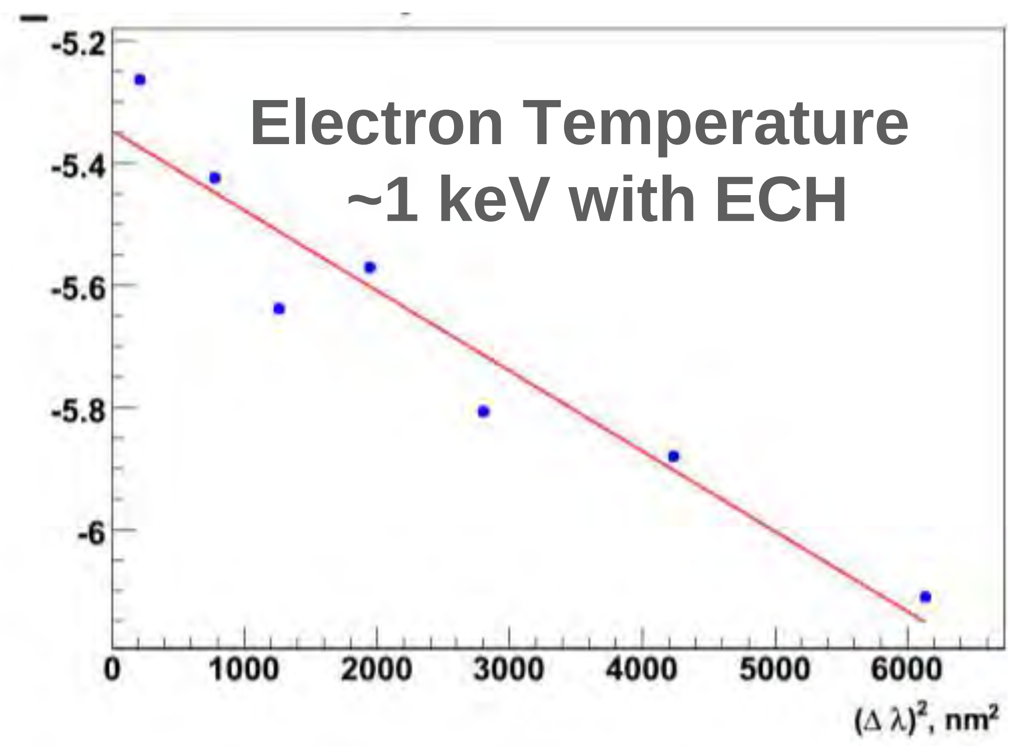
So what has changed?

Hint: axisymmetric physics breakthroughs, HTS Magnets, computation, and 40 years of advancement of fusion technology

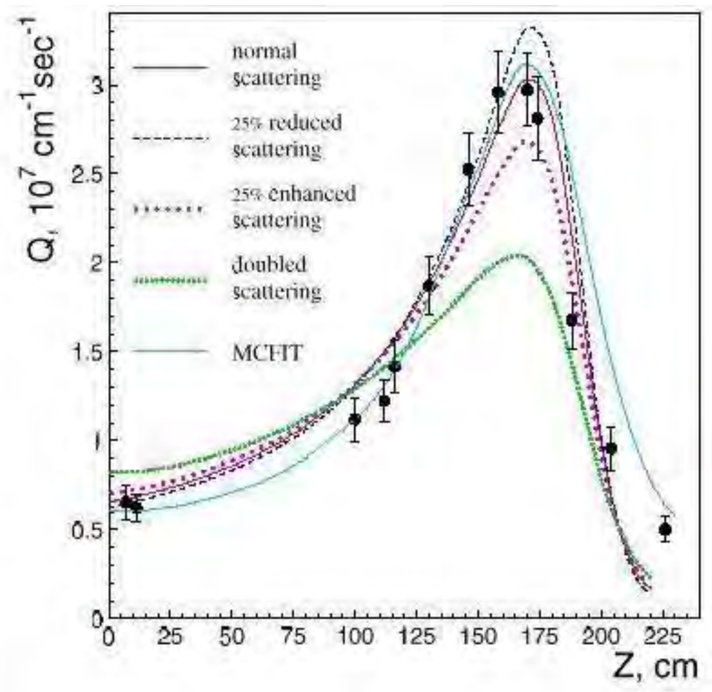
Three (*four!*) myths about axisymmetric mirror performance have been shattered by the GDT device in the past decade







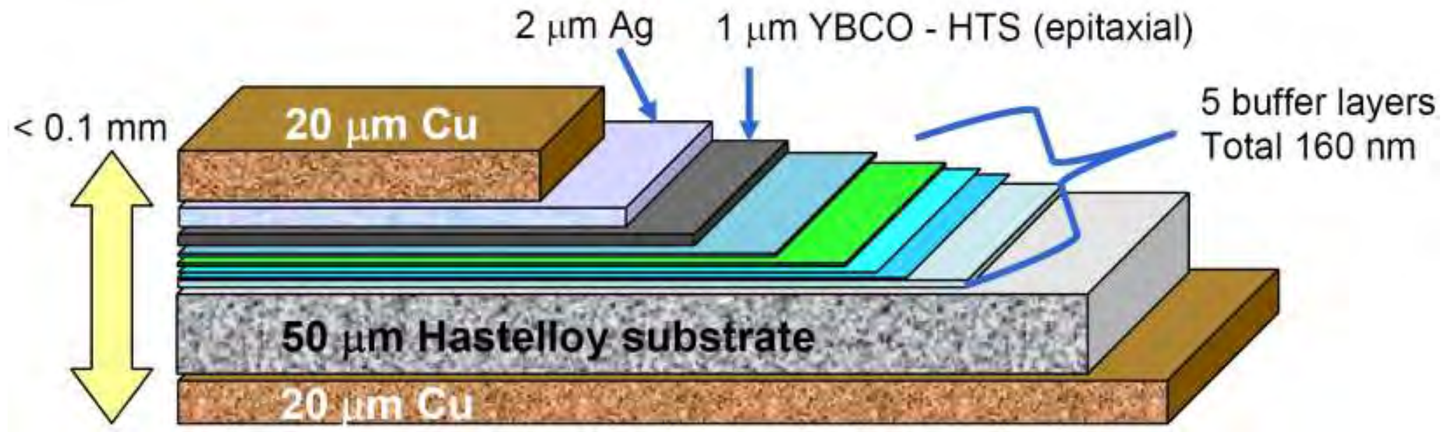
neutron yield profile

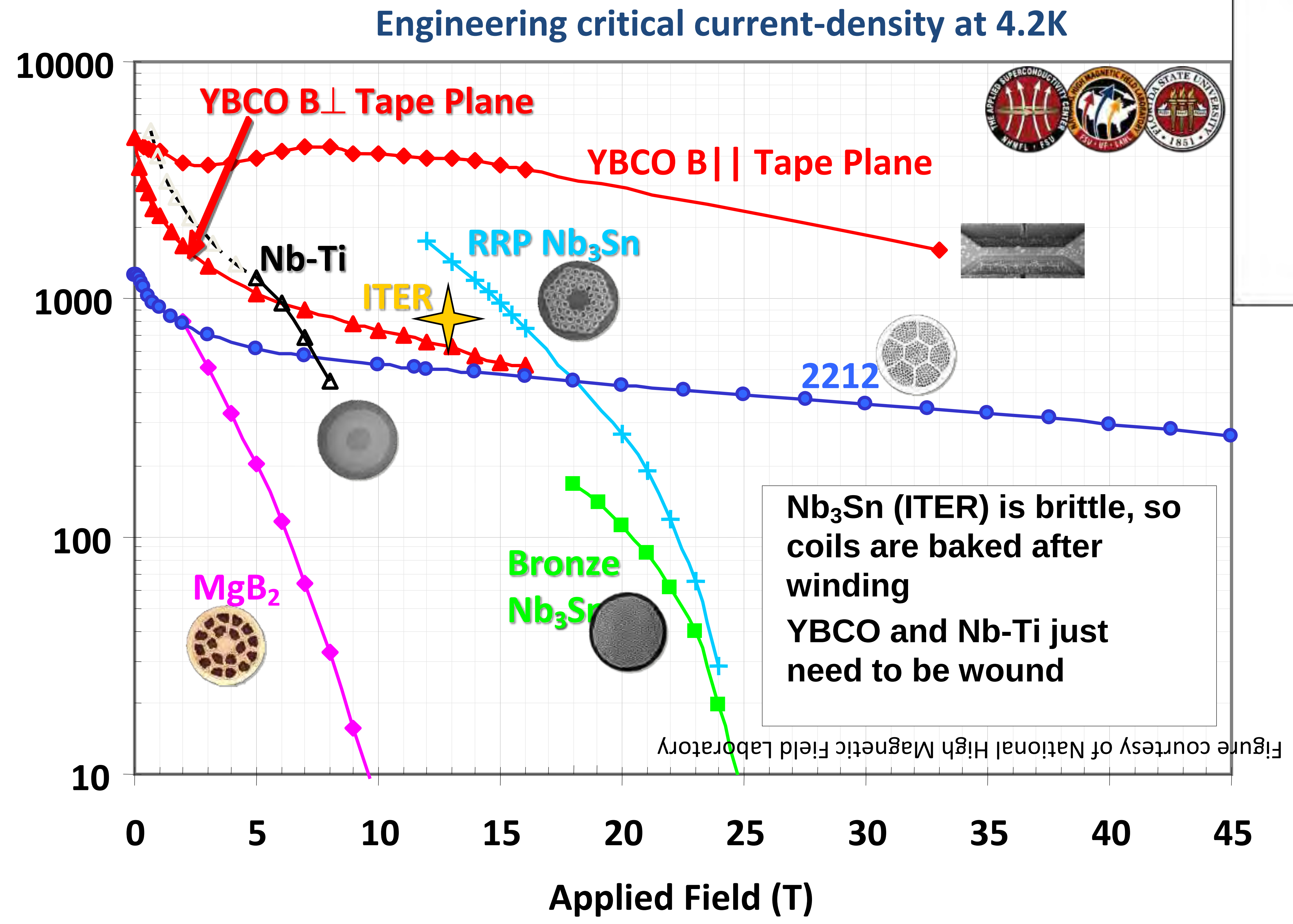


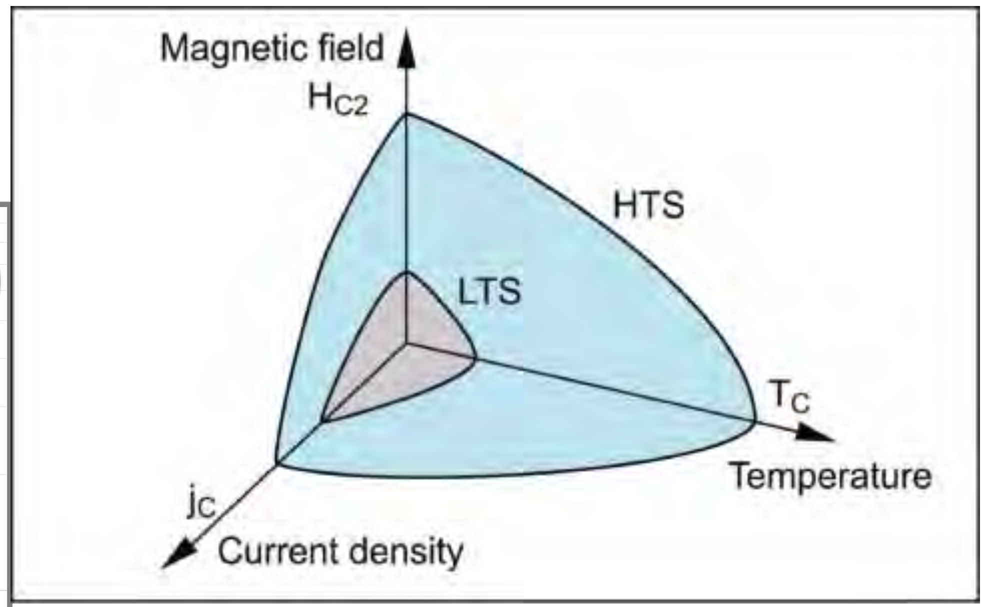
1. Axisymmetric mirrors can't overcome interchange: high pressure observe ($\beta \sim 0.4$)
2. Electrons in mirrors are always cold: high electron temperatures $T_e \sim 1keV$ generated with ECH and ambipolar confinement
3. Non-thermal plasmas are always unstable to micro instabilities: classical fast ion confinement and fusion products observed (no kinetic instability)

4. *mirror reactors must be complicated: ATM reactor is possible!*

High Temperature Superconductors are a game-changing technology for Magnetic Mirrors: Higher mirror ratio, high pressure (and fusion power), more compact

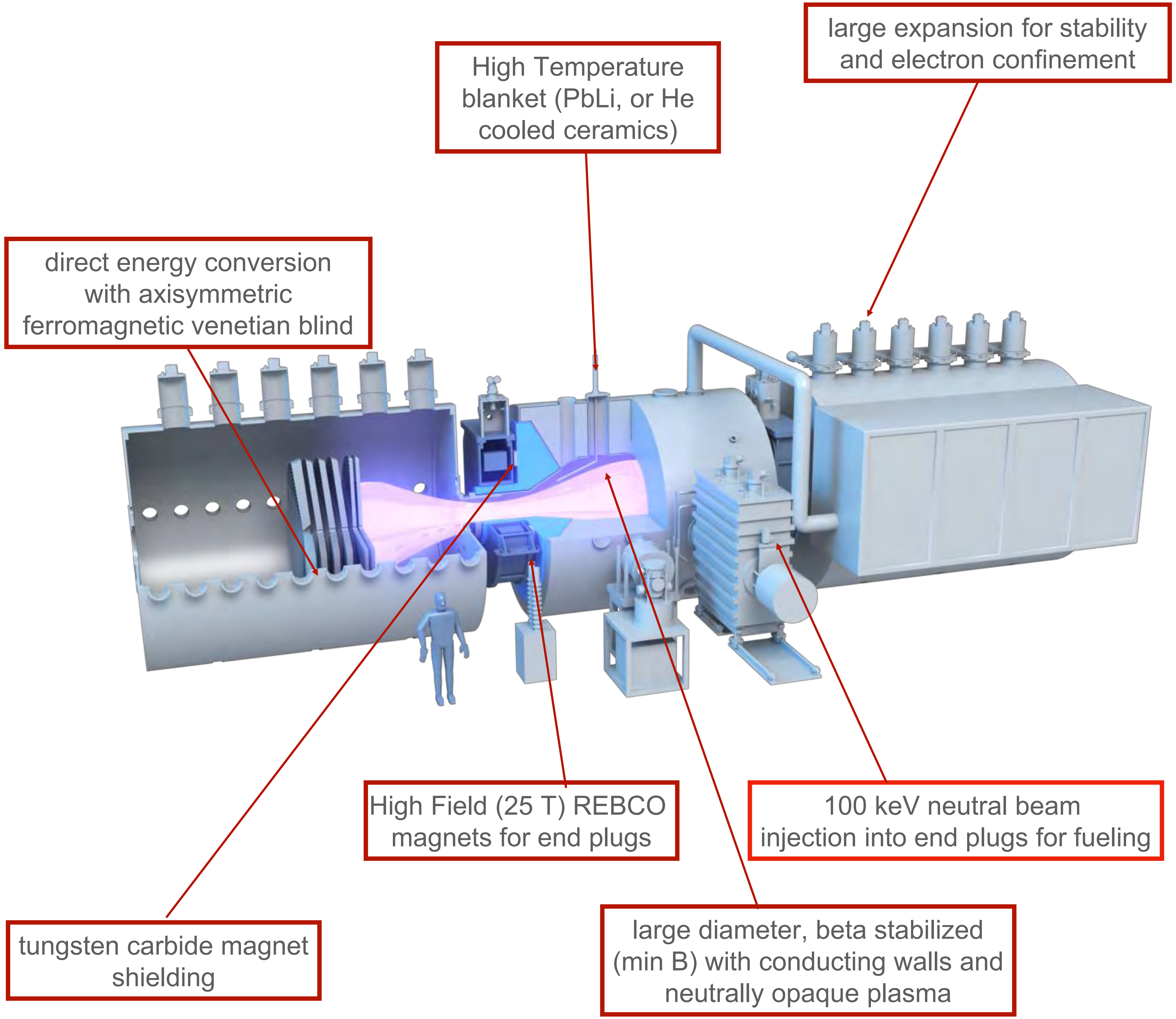






New developments in superconductor technology mean a smaller, more maintainable fusion reactor than the ITER-like reactor that was previously envisioned.

ARC = 1/10 Iter using twice the field



Aspirational WHAM++

WHAM ++

B_M=25 T, B_0=2.5 (5) T, a = 0.5 m
P=2-5 MW (>100 keV NBI) CW and DT
Q ~ 3 (6-15 MW of fusion power)
R_M=15 at β=0.5
Shape optimize: short fat, with divertors
saddle coil feedback

WHAM+

-full power performance verification of end plug
-test direct energy conversion boost to Q~6-10

WHAM++

steady-state operation with dt
High temperature blanket testing (PbLi)

Cost (driven by magnets)
ca. $50M of Rebco tape (approx. 2 SPARC TF coils)

Advanced Energy Recover makes electrical breakeven feasible for the mirror with good choices

direct conversion efficiency

$$\eta_{DC} \sim 0.8$$

$$\eta_T P_{Fus} = P_{Loss}\left(\frac{1}{\eta_H} - \eta_{DC}\right)$$

$$\eta_T \approx 0.45$$

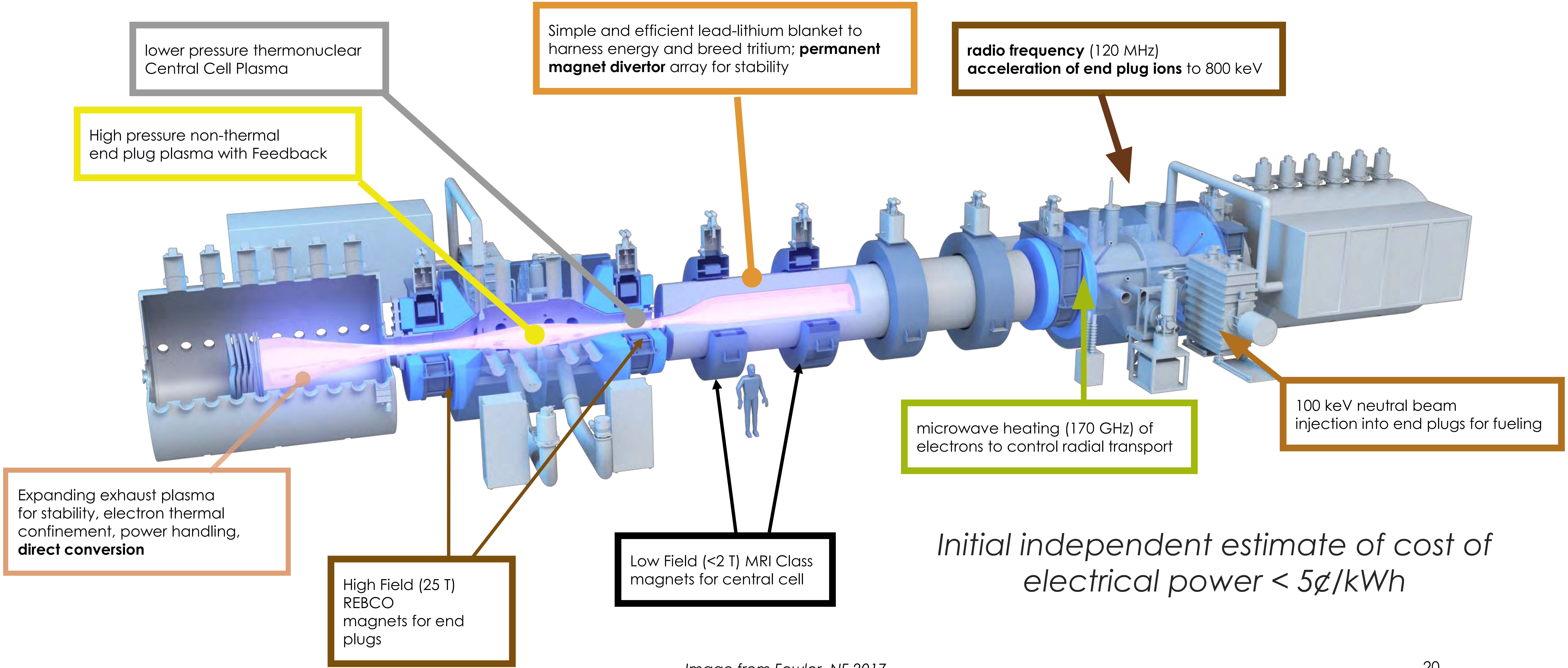
High temperature (550 C) immersion blanket with Brayton cycle for efficiency

RF	$\eta_H = 0.8$	~2$/watt
NBI	$\eta_H = 0.6$	>5$/watt
ECH	$\eta_H = 0.6$	10$/watt

$$\frac{P_{Fus}}{P_{loss}} > \left(\frac{1}{0.8} - 0.8\right)/0.45 \sim 1$$

High-Field Axisymmetric Magnetic Mirror (HAMMiR)

*The **lowest capital** and **least complex** fusion reactor suitably scaled for industrial use*



Initial independent estimate of cost of electrical power < 5¢/kWh

Image from Fowler, NF 2017

WHAM is a ARPA-E funded and aims to prototype the ATM end plug

Physics Missions:

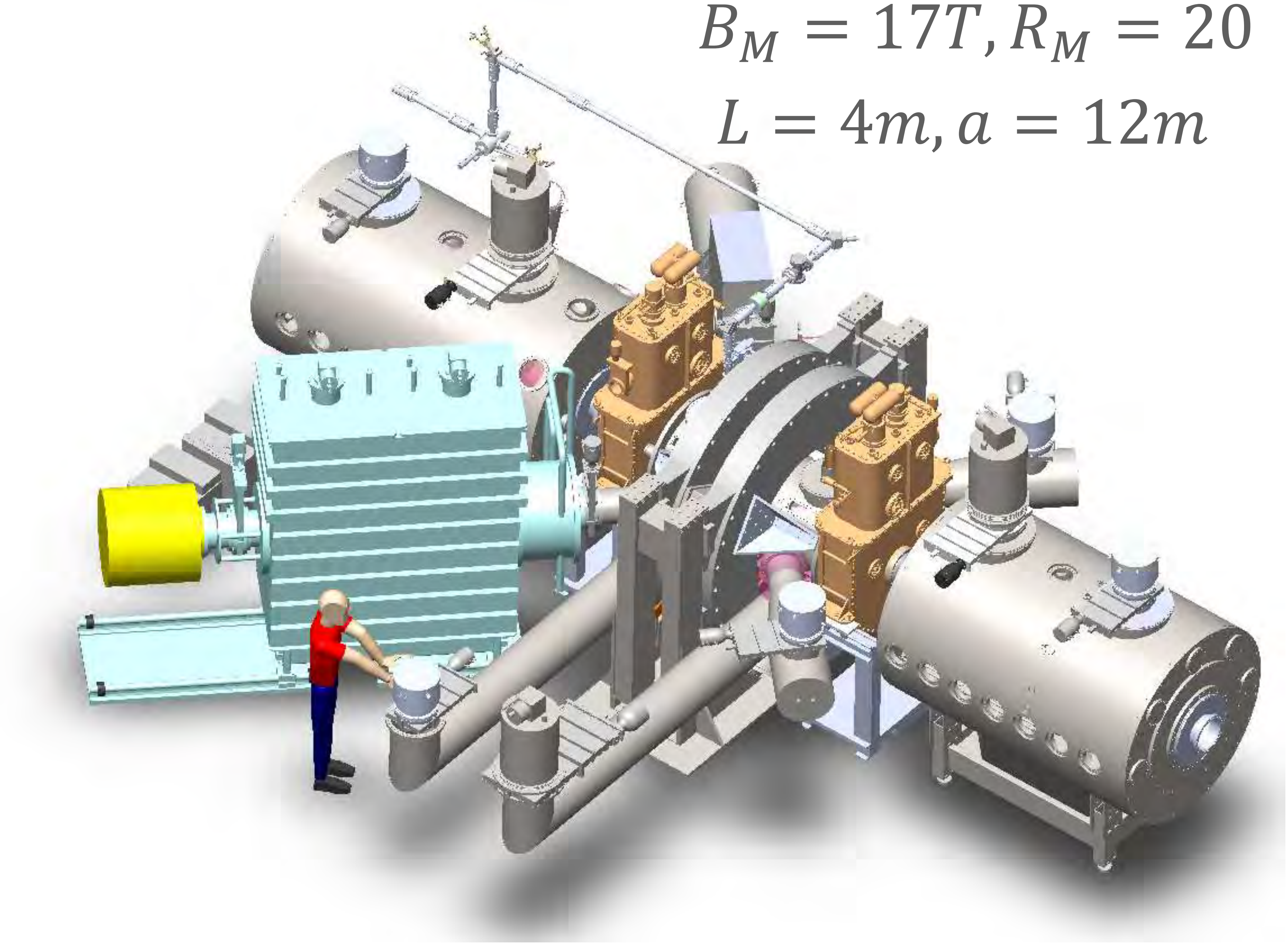
1. *Confine MHD stable, high Te plasma in axisymmetric mirror*
   - demonstrate *v*ortex stabilization combined with electron heating and expander confinement
   - create high plasma pressure allowed by strong magnetic field
2. *Demonstrate novel in-situ ion acceleration*
   - combine radio-frequency heating with neutral beam fueling
   - show confinement benefit of high energy ions

Technology Missions: (intertwined with physics goals)

1. *Build REBCO HTS mirror reactor magnets*
   - build and operate 17 T, 5.5 cm bore HTS coils
   - design 25 T, 50 cm integrated end plug for WHAM++, Hammir
2. *Demonstrate advanced particle handling techniques*
   - Novel non-evaporable tantalum getters
   - test advanced plasma facing components

$B_M = 17T, R_M = 20$

$L = 4m, a = 12m$

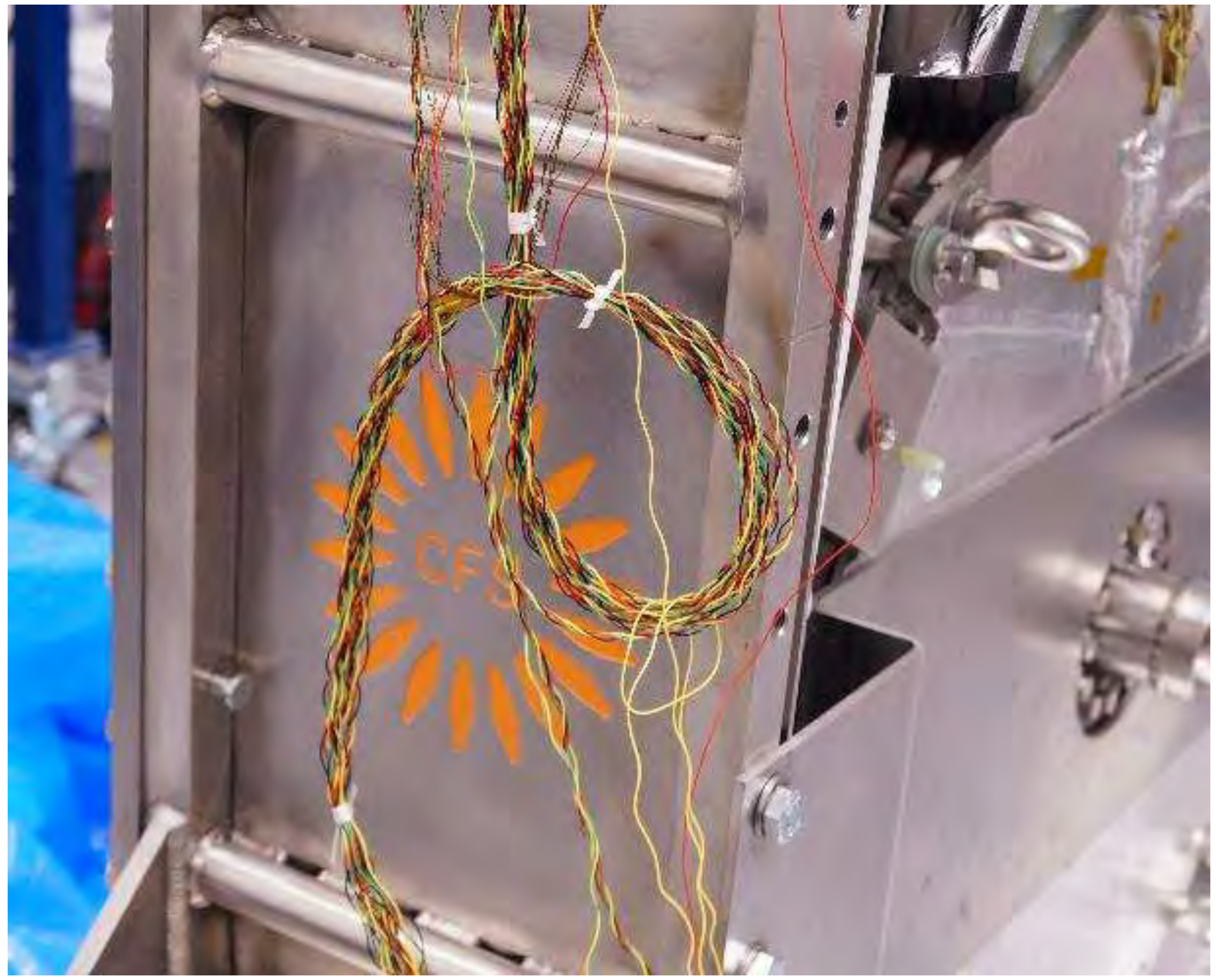


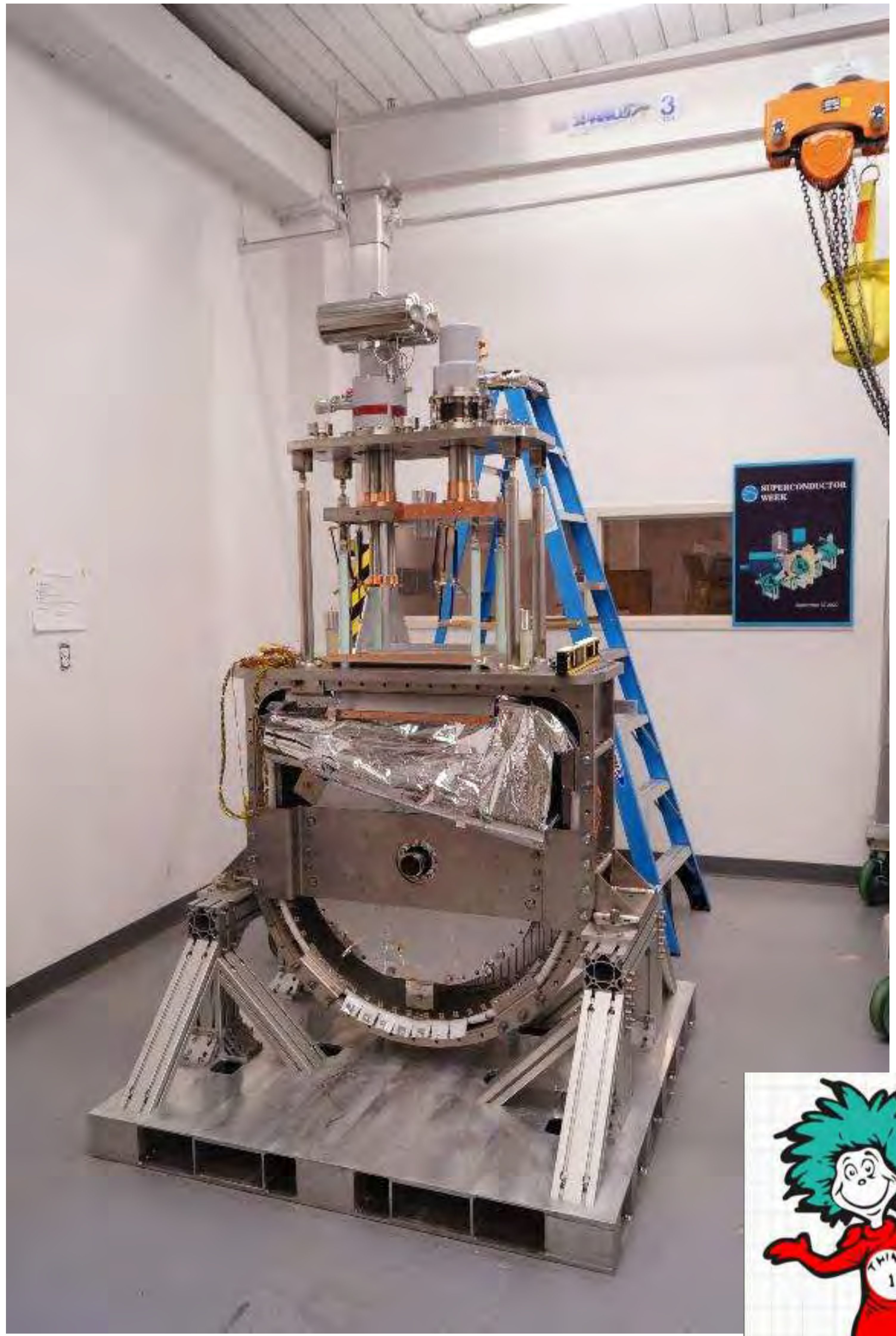
Additional ARPA-E directives:

1. *Refine reactor concept*
   - low cost/length central cell solution
   - neutronics analysis for shielding
2. *Develop commercialization plan*

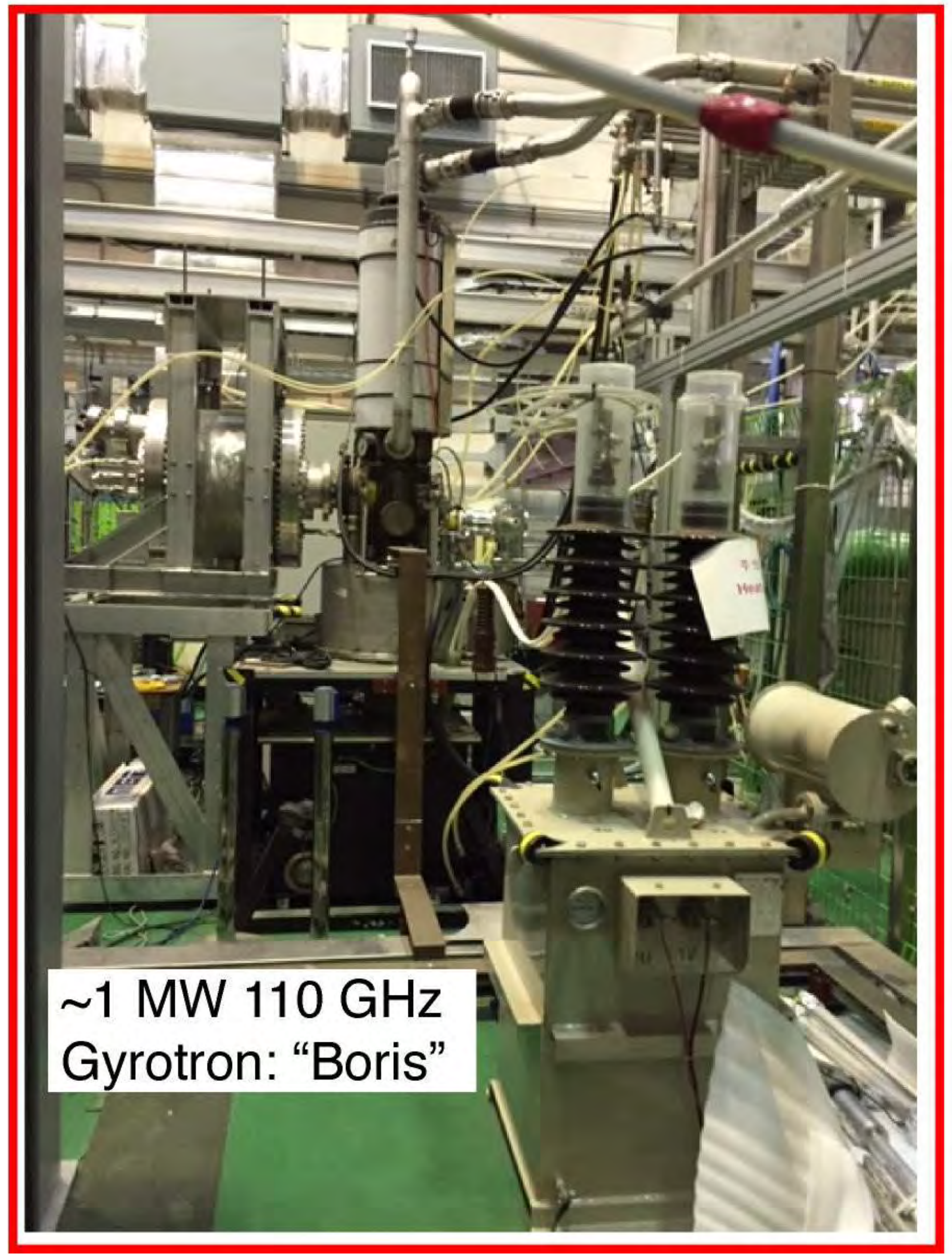
WHAM magnet specifications (Thing 1 is testing next week)

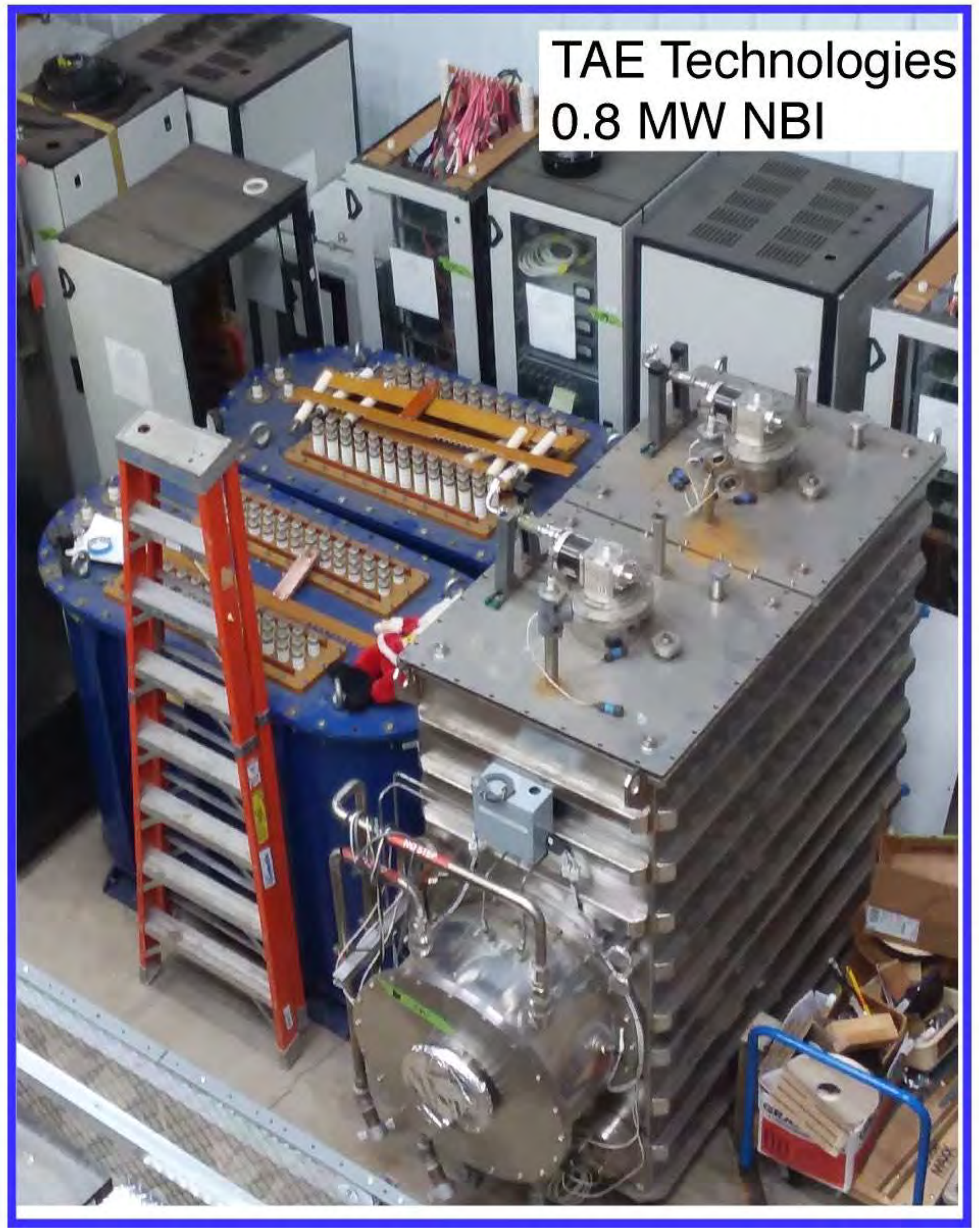
Stored energy	3.2	MJ
Magnetic field at center	17	T
Maximum magnetic field	20	T
Operating current	2000	A
Inner diameter	0.05	m
Outer diameter, WP	0.7	m
Thickness	0.15	m
Height	2.1	m
Winding pack mass	500	kg
Magnet mass	1500	kg
Operating temperature	20	K

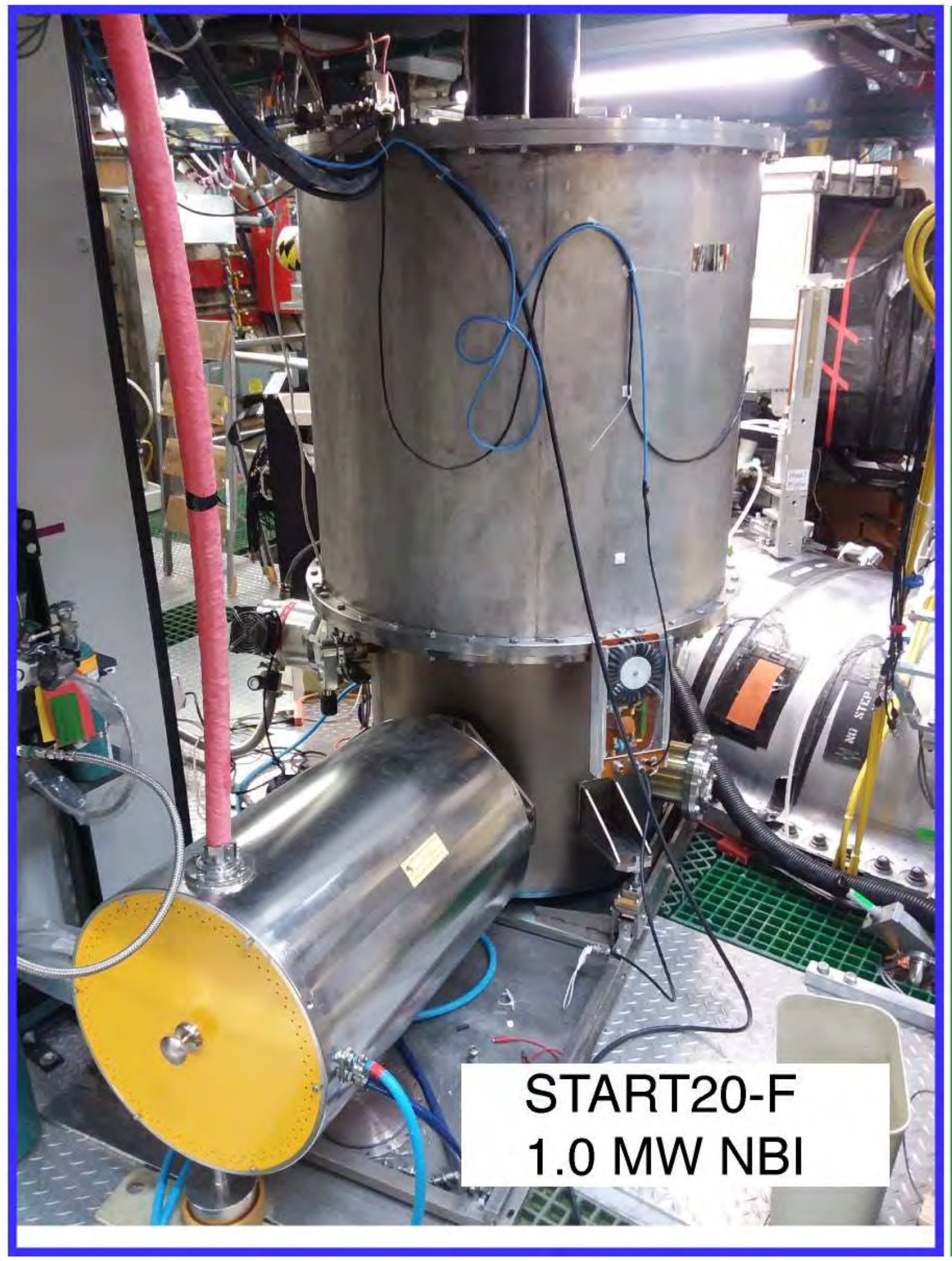




WHAM is recycling used heating systems to create and control high $T_e, \langle E_i \rangle$ plasmas





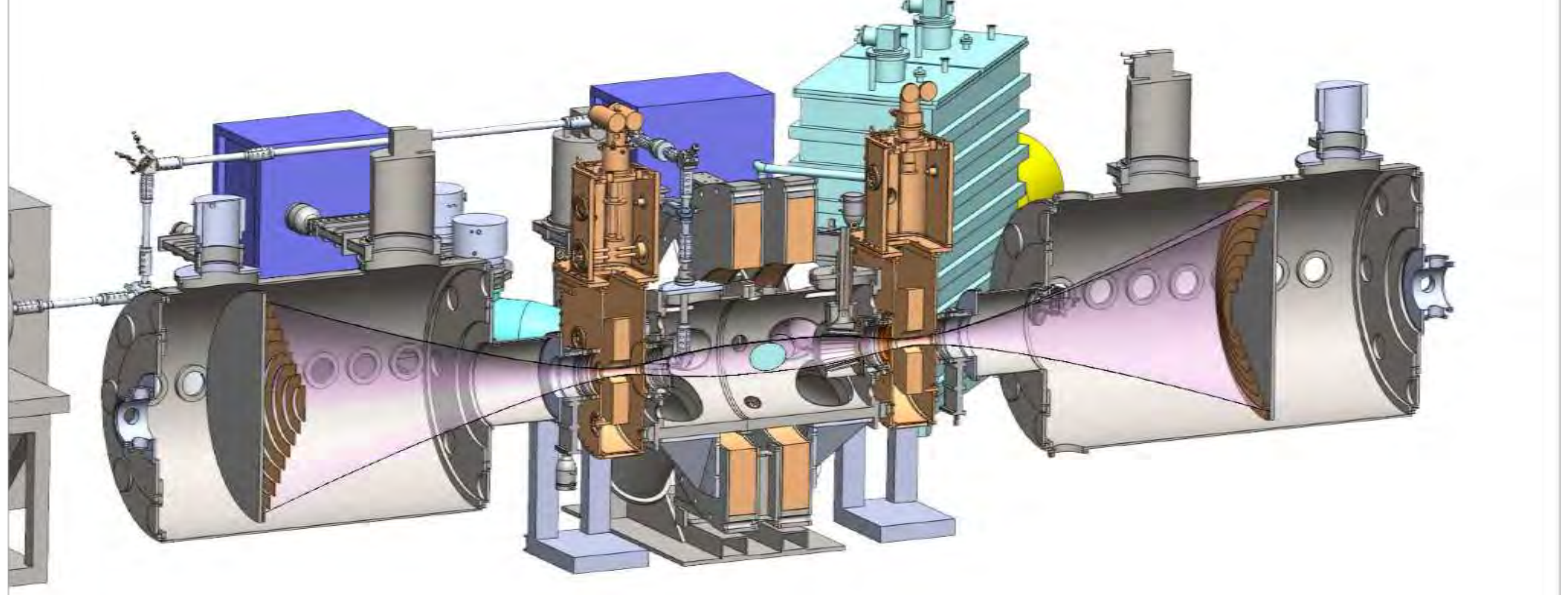


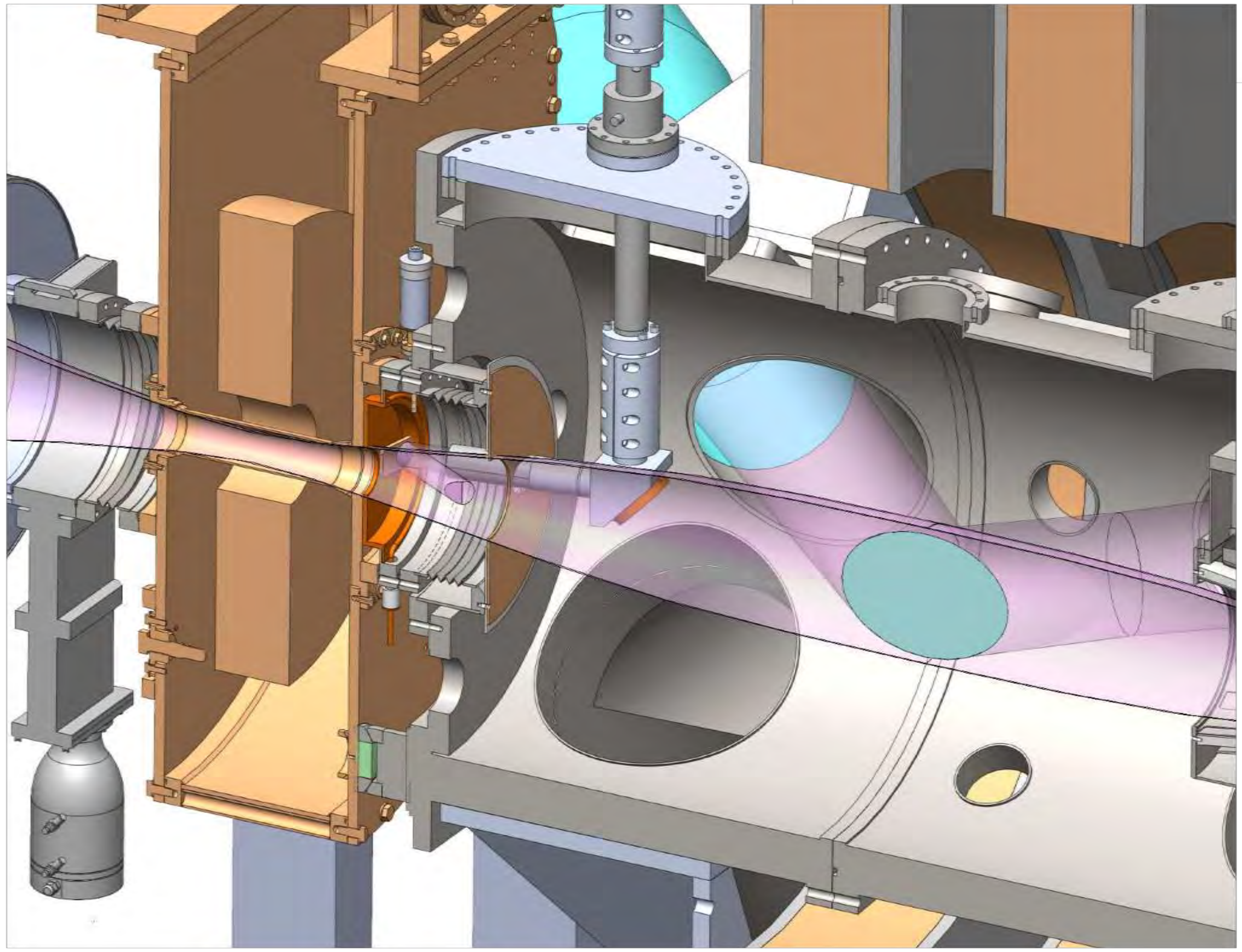
$P_{ECH} \leq 1 MW$
$\tau_{ECH} = 20\, ms$
$f_{ECH} = 110 GHz$

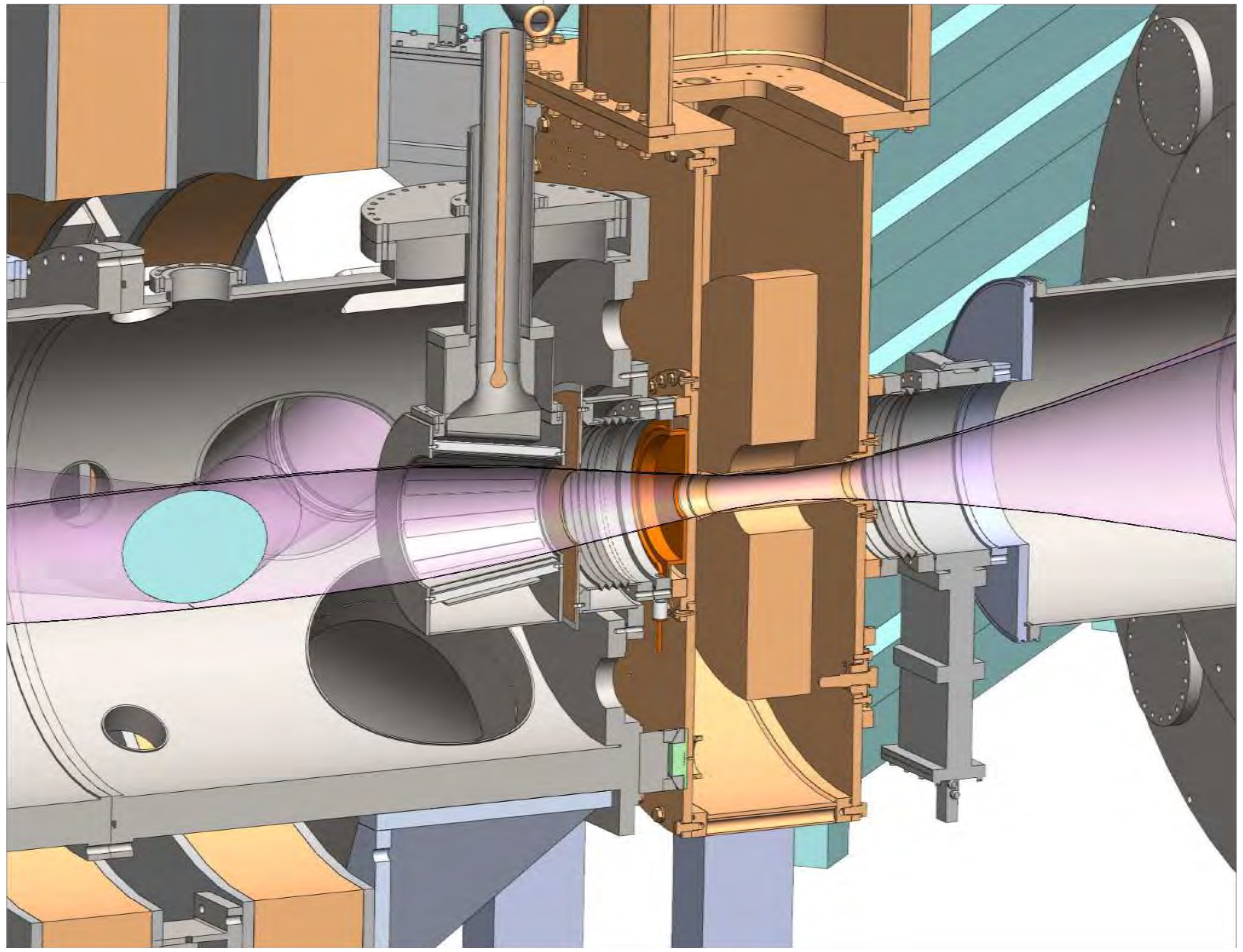
$P_{NBI} \leq 1 MW$
$\tau_{NBI} = 50\, ms$
$E_b \sim 25 keV$

$P_{rf} \approx 1 MW, \tau_{rf} = \infty$

$f_{rf} \approx 4 - 26 MHz$

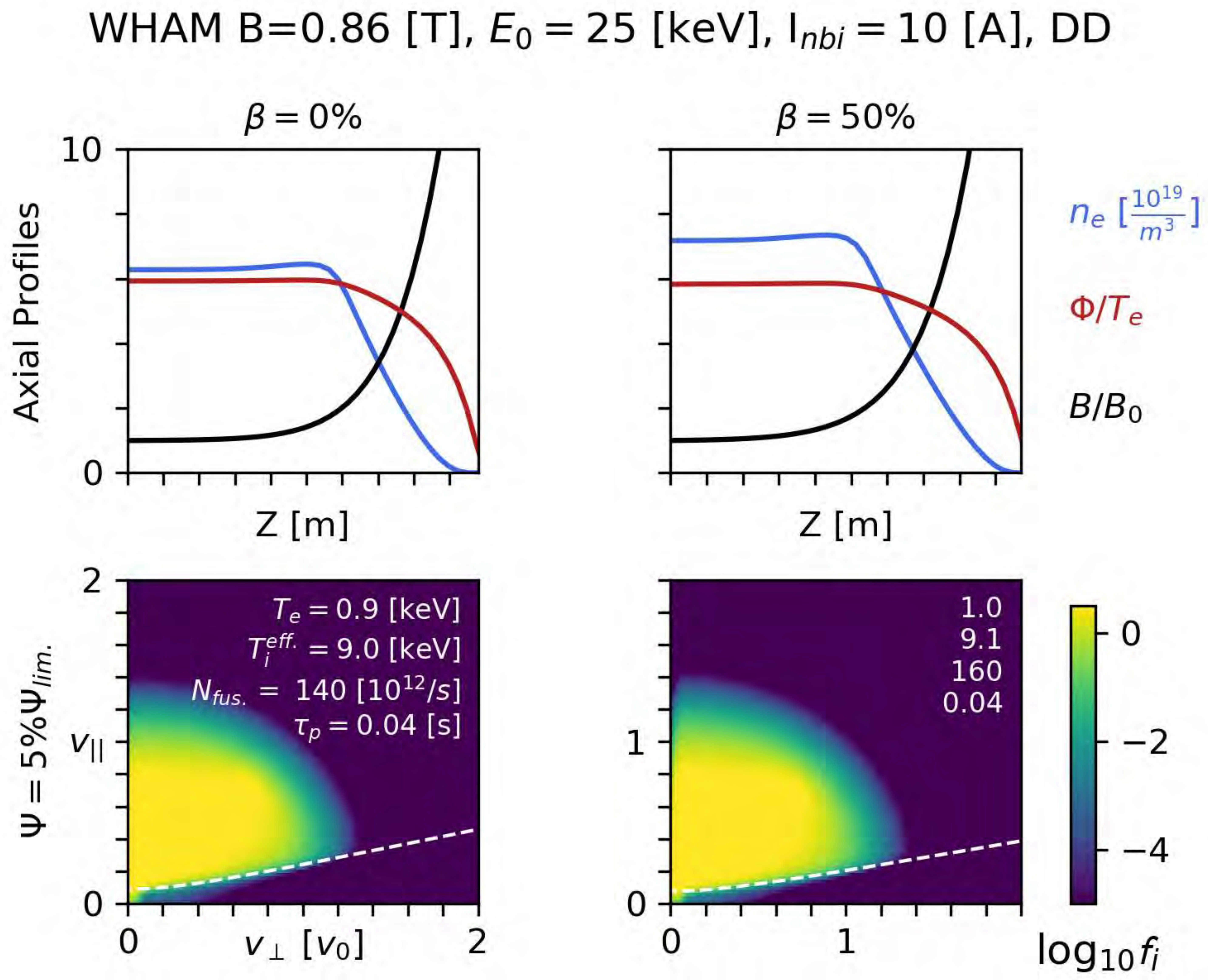




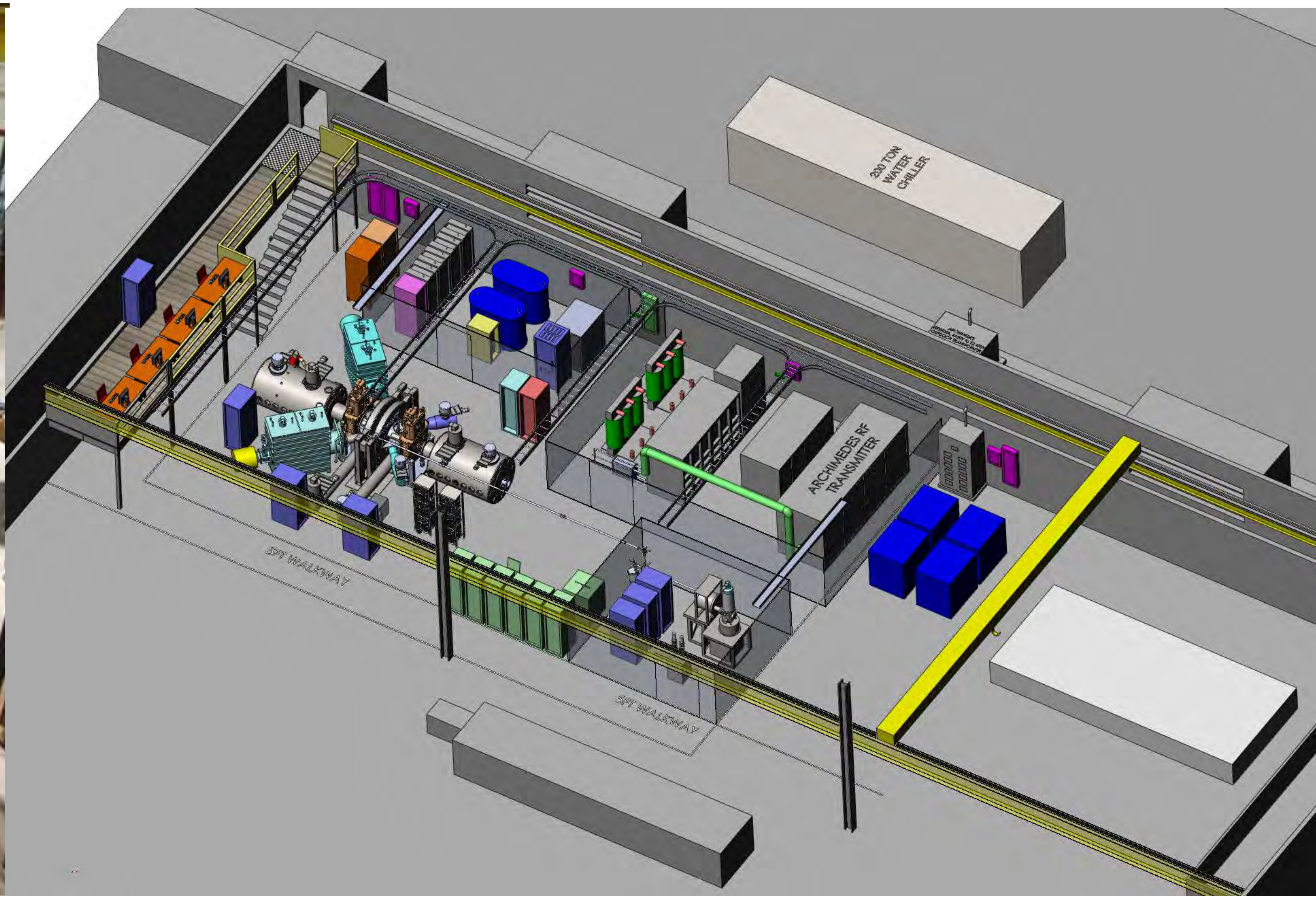


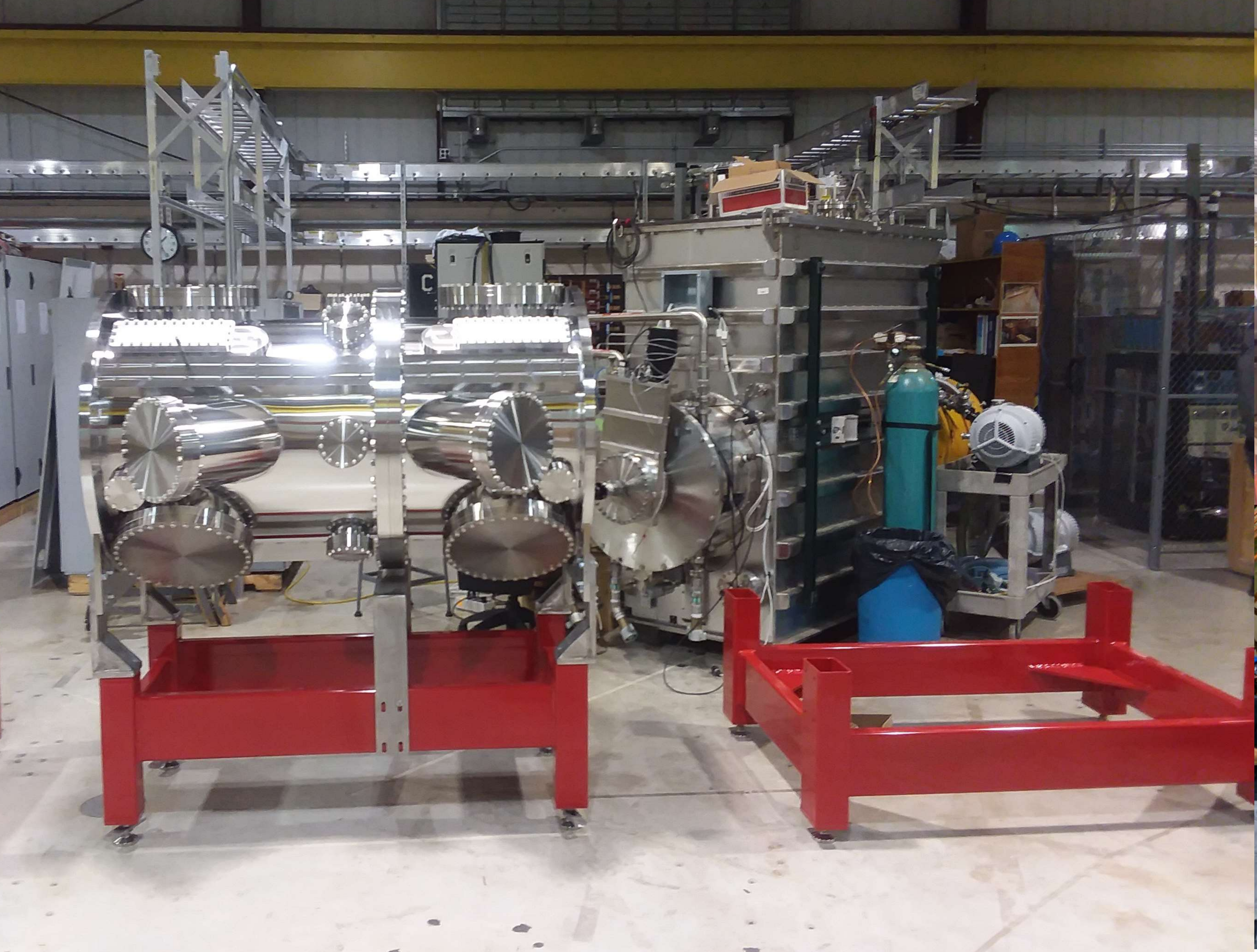
Mild sloshing ions help fill ambipolar hole (solve DCLC)

T_e=1 keV, T_i=10 keV, n=6x10^{19} m^{-3}, τ_P=40 ms, S_{dd}=10^{14} n/s



WHAM is now under construction at the Physical Sciences Lab of the University of Wisconsin: First plasma expected summer 2022






WEST

REALTA FUSION

INDUSTRIAL HEAT & POWER FROM FUSION

Lowest capital, least complex path to commercially competitive fusion energy

Focus on Plant #1 in industrial process heat

End of talk

Thank you for your attention and please help us !

Team

Cary Forest, PhD

Leading plasma physics and fusion innovator with industry (General Atomics) and academic background. Heads Wisconsin plasma physics lab. U.Wisconsin Professor, Princeton PhD, Fellow of American Physical Society.

Jay Anderson, PhD

A highly accomplished and world-recognized researcher in fusion plasma physics. Specialties include auxiliary plasma heating and stability, Jay addresses the critical scientific issues facing the magnetic mirror fusion reactor.

Kieran Furlong, MBA

Experienced start-up operator and venture capital investor. Chemical engineer with background in high temperature process catalysis (ICI, Johnson Matthey) and climate-tech. Stanford MBA.

Ben Lindley, PhD

Industry-experienced nuclear engineer (Jacobs) and now a faculty member at U.Wisconsin, Ben played a key role in the development of software for the analysis of boiling water reactors, sodium-cooled fast reactors, and molten salt reactors.

Oliver Schmitz, PhD

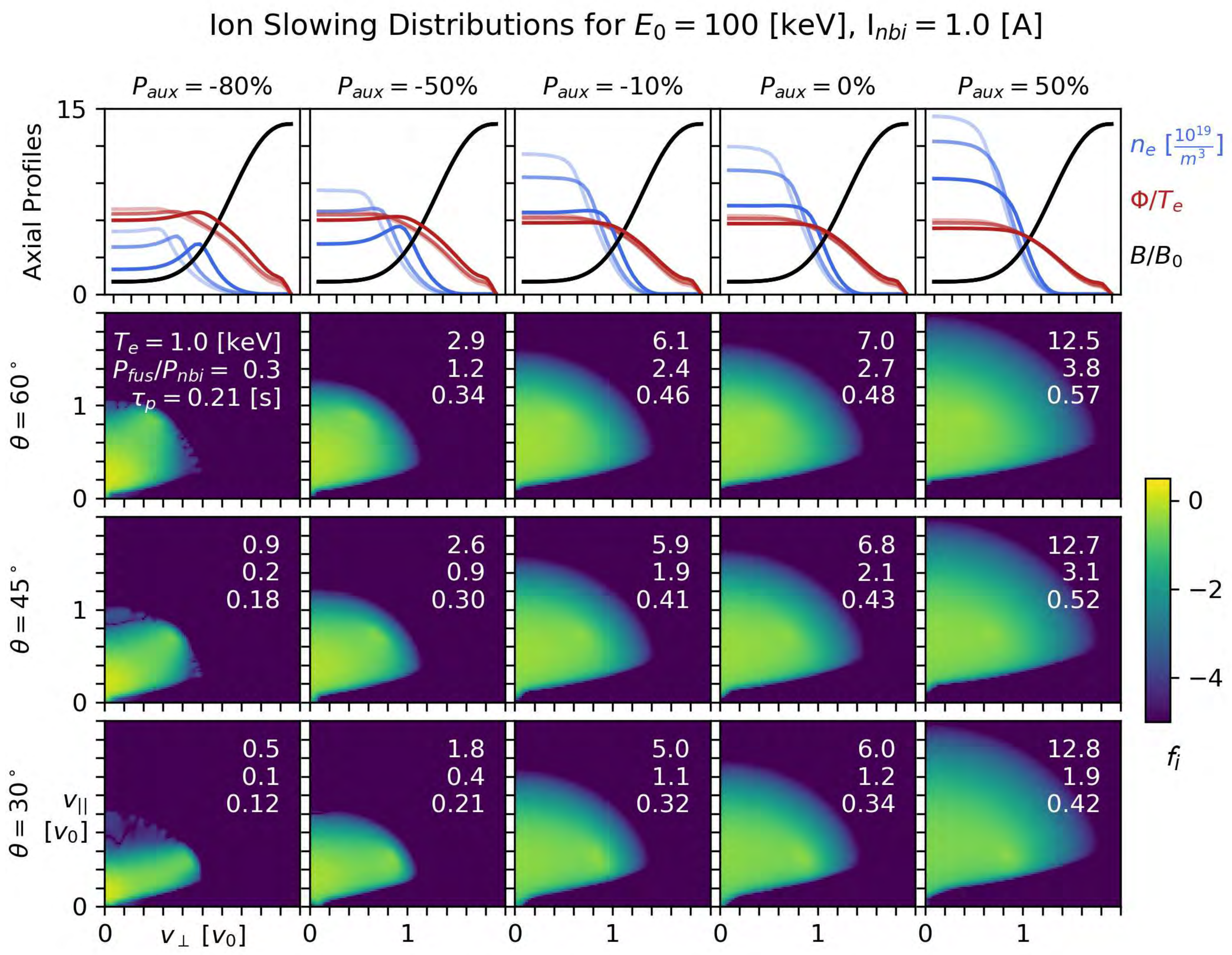
Expert on high temperature fusion plasma & wall material interactions. U.Wisconsin Professor & Dean of Research, ITER Science Fellow.

Wisconsin
University of Wisconsin–Madison

WARF


WHAM
Wisconsin HTS Axisymmetric Mirror
UW Physics, Engineering Physics and Physical Sciences Lab
Jan Egedal
Cary Forest
Jay Anderson
John Wallace
Steve Oliva
Jeremiah Kirch
Mike Clark
Oliver Schmitz
Alex Squitieri
Roderick MccNeil
Mary Severson
Students
Kunal Sanwalka
Danah Velez
Douglass Endrizzi
Oscar Anderson
Jake Murawski
Jon Pizzo
Post Docs
Mykola Ialovega
MIT and CFS
Sergey Kuznetsov
Alexey Radovinsky
David Meichle
Alex Zhukovsky
Dennis Whyte
Mark Stowell
Grant Kristofek
Charlie Sanabria
Blake Mitchell
Dan Nash
Nick Kelton
Bob Mumgaard
Abhay K Ram
Cornwall Lau
MIT rf C
John C Wright
Atul Kumar
Bob Harvey
GA ECH hardware
Ethan Peterson
Dylan Copeland
Yuri Petrov
Charles Moller
Juan Francisco Caneses Marin
David Green ORNL
John Lohr

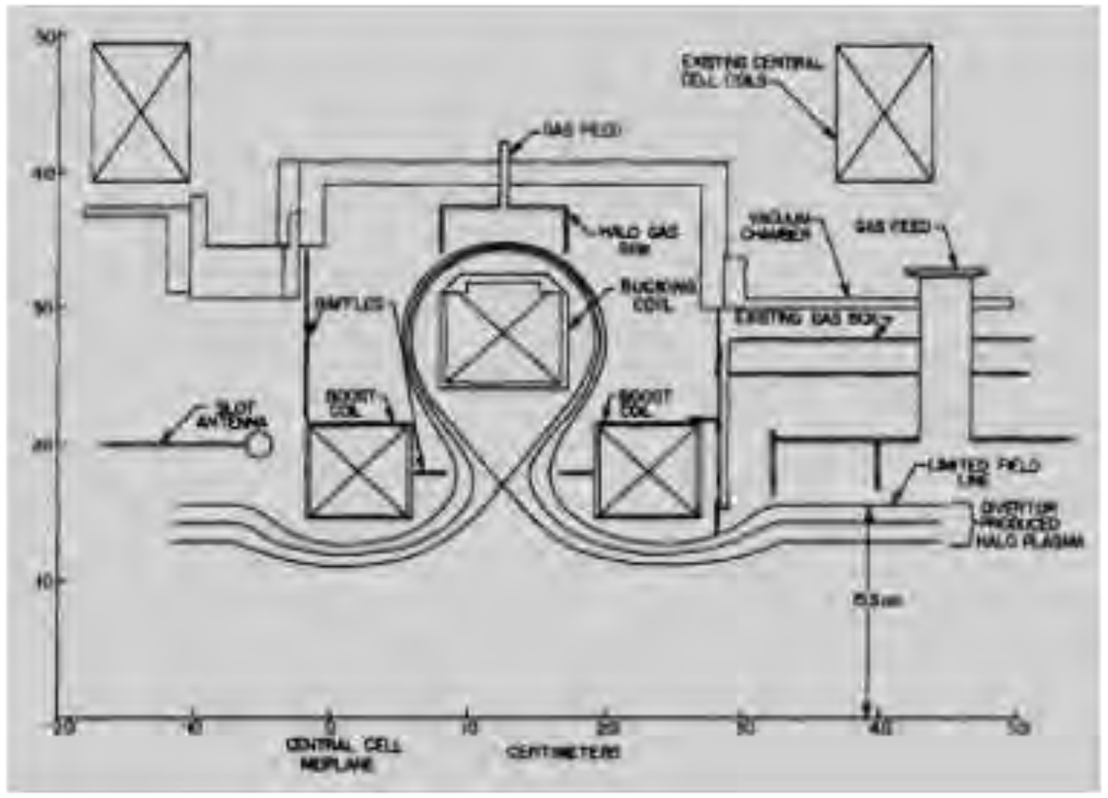
Bounce-averaged Fokker Plank solution show tradeoffs with beam injection angle and role of extra electron cooling (or heating)



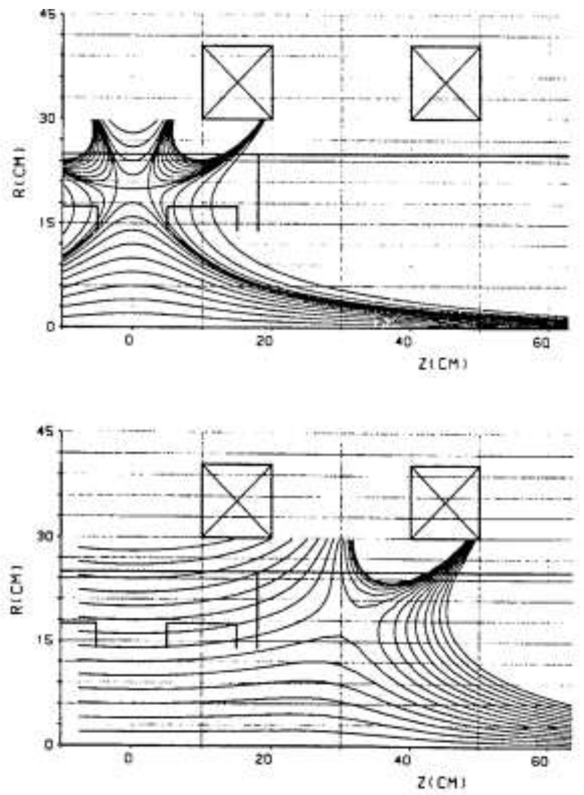
Shaping and feedback will be used for confinement and stability optimization

High β $p_{\perp} \neq p_{\|}$ solution to Grad-Shafranov equilibrium

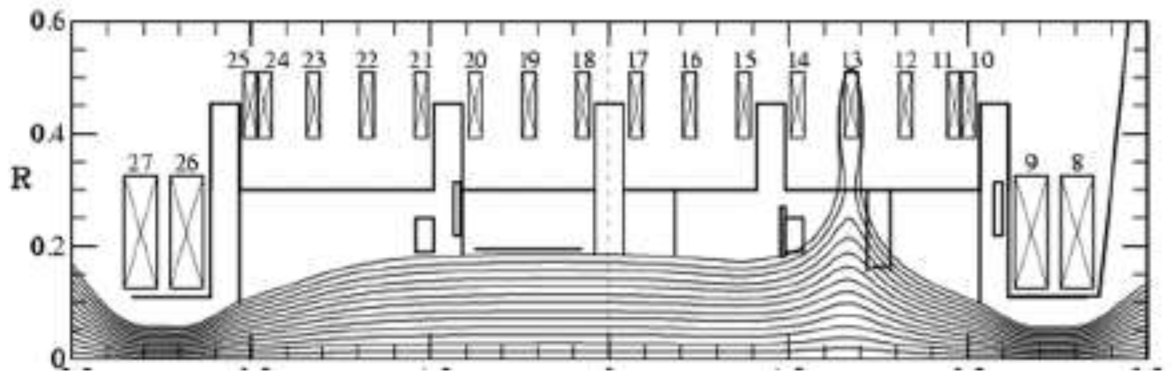
Divertor Stabilization (electrical short-circuit for m=1 mode)



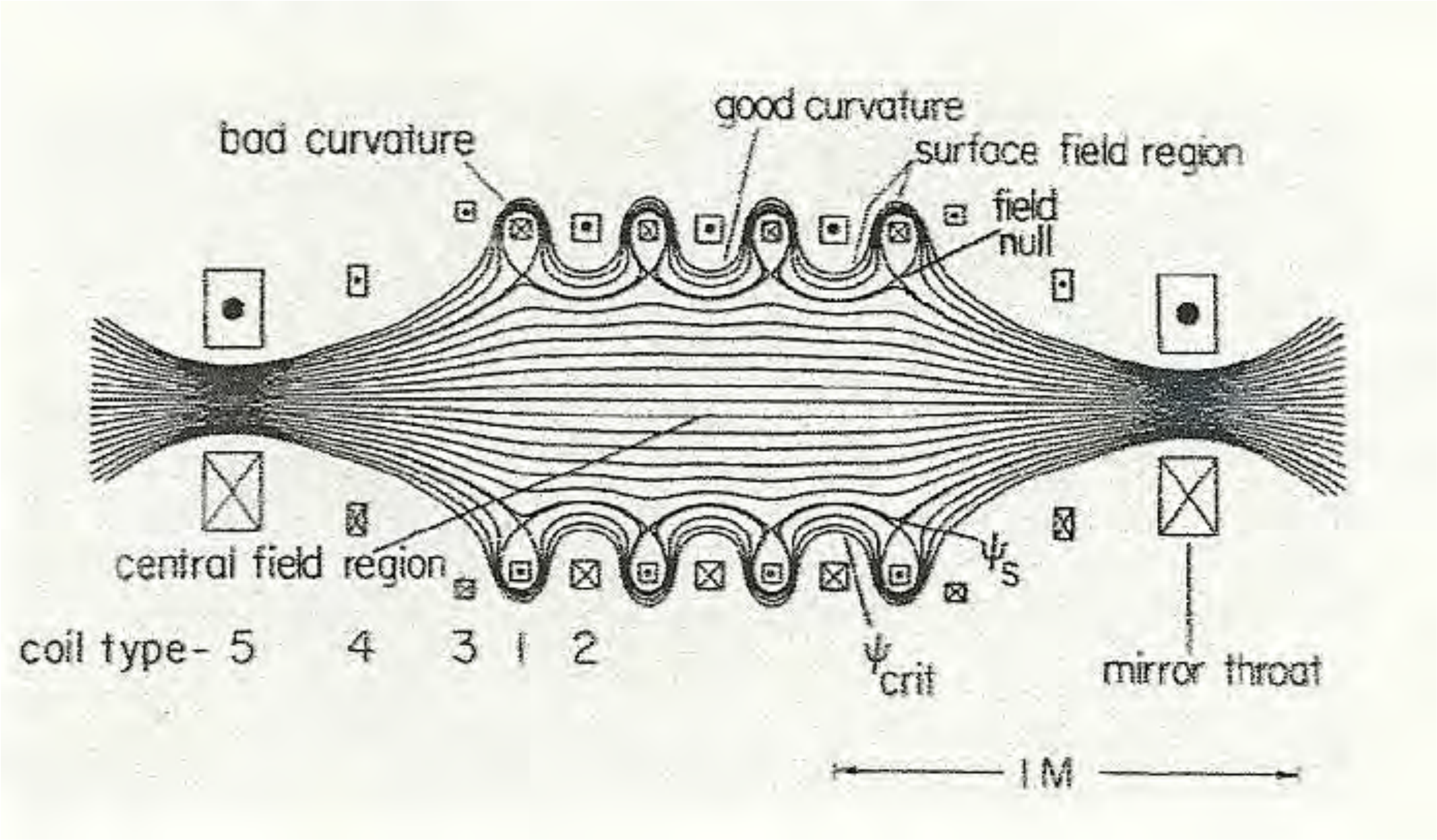
Tara



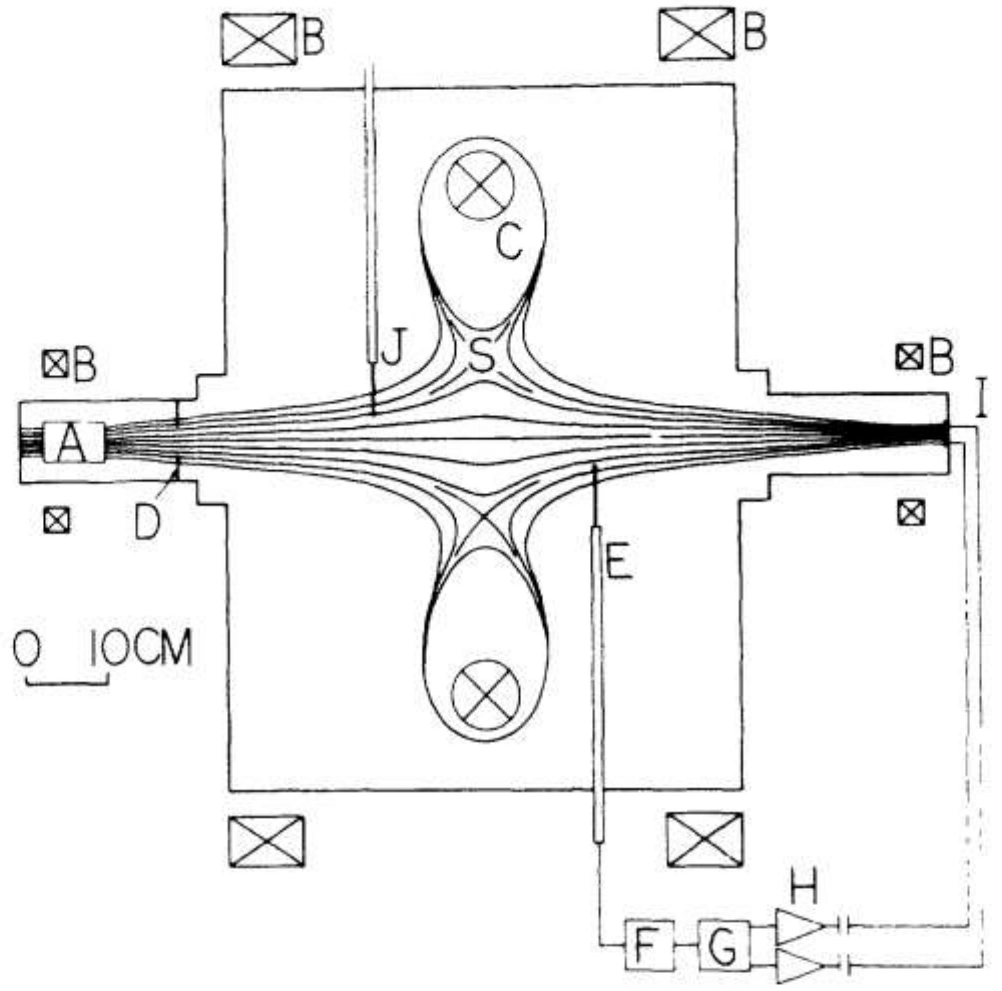
HIEI



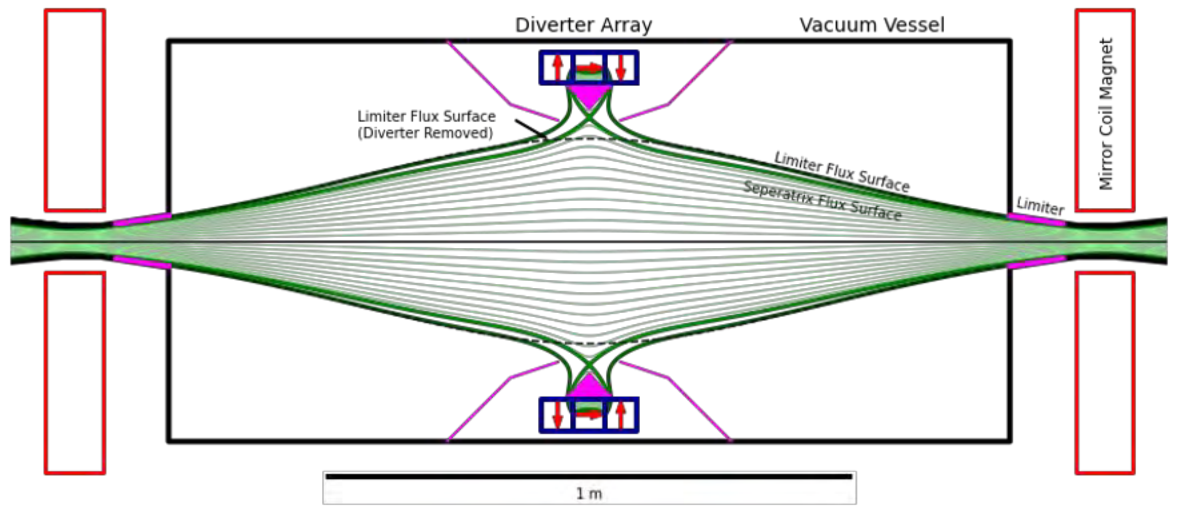
Hanbit



LAMEX



Stable with separatrix; unstable with limiter

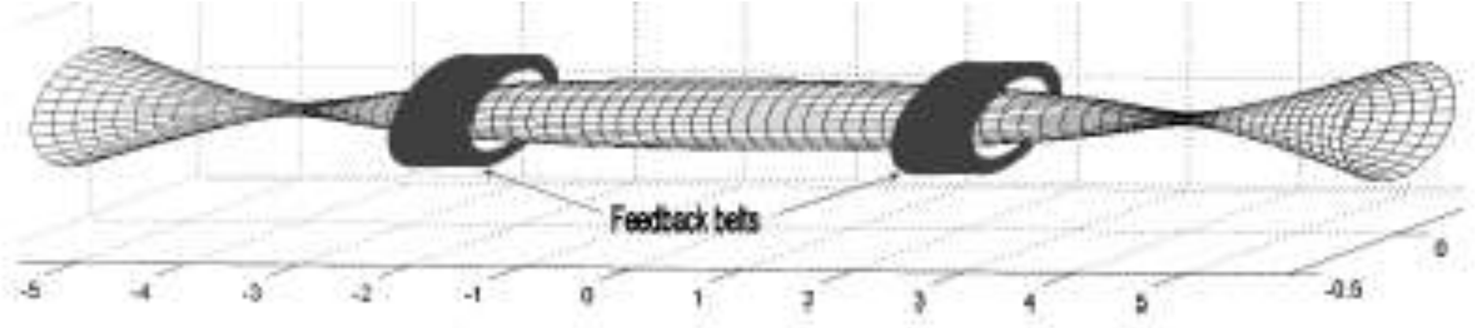


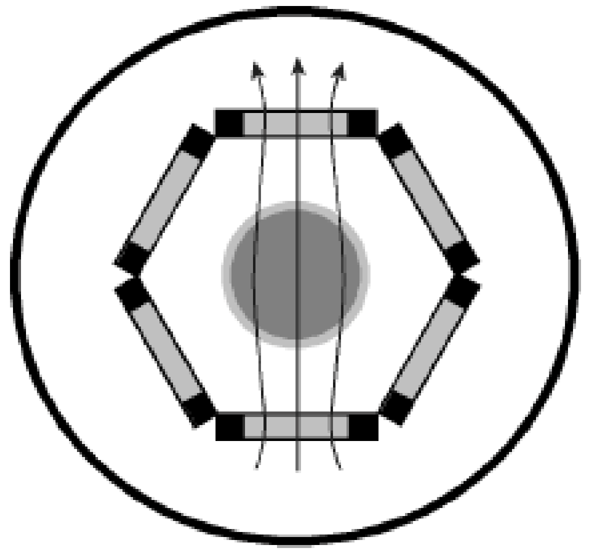
Permanent magnet configuration

Prater, R. Feedback Suppression of a Large-Growth-Rate Flute Mode. *Phys Rev Lett* **27**, 132–135 (1971).

Feedback

Beklemishev, A. D. Tail-Waving System for Active Feedback Stabilization of Flute Modes in Open Traps. *Fusion Sci Technol* **59**, 90–93 (2017).





Rotating Field

Stabilization of magnetic mirror machine using rotating magnetic field

Omri Seemann[1]†, I. Be'ery[2] and A. Fisher[1]

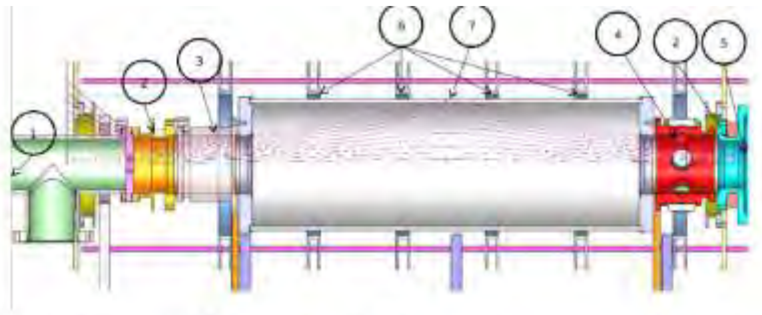
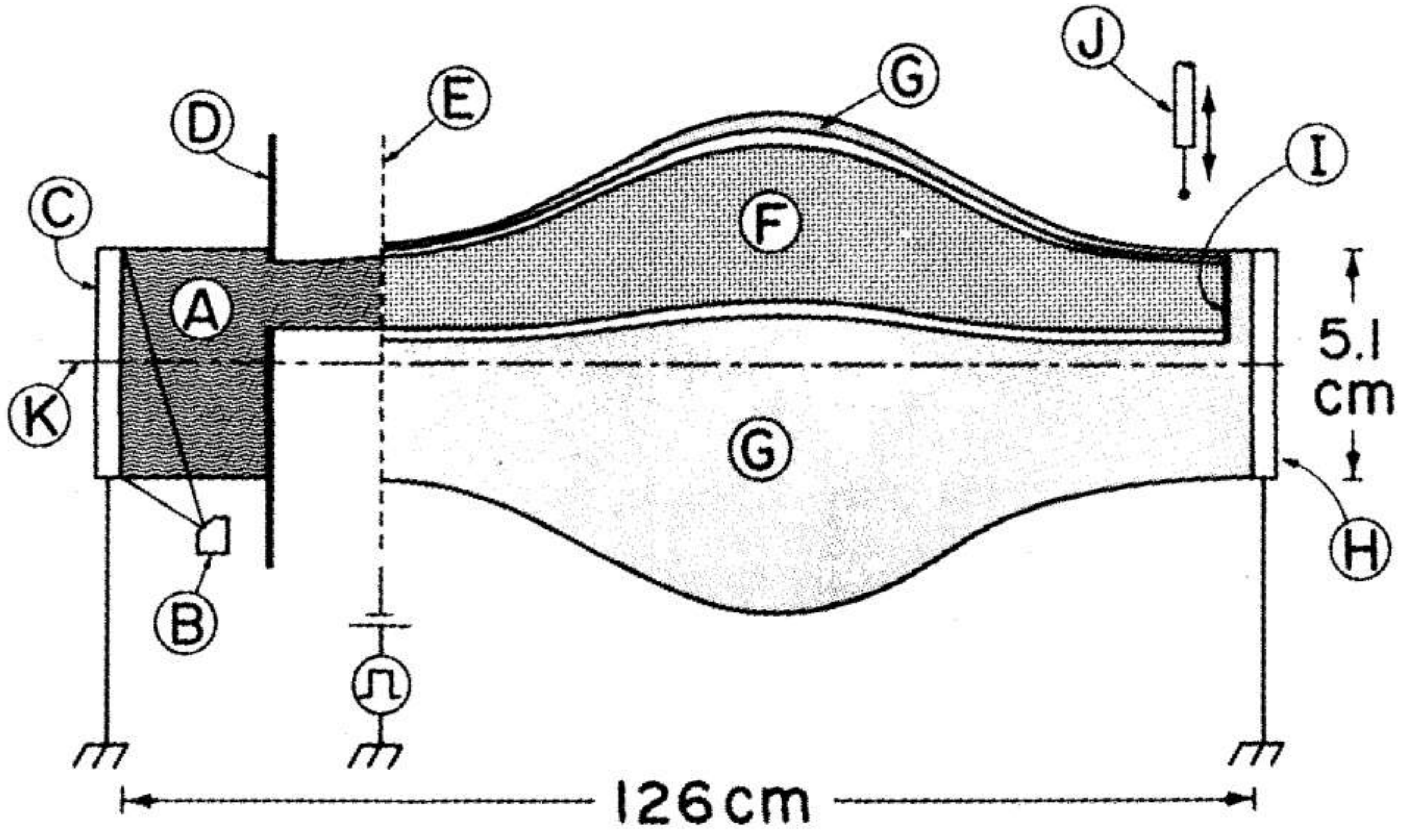


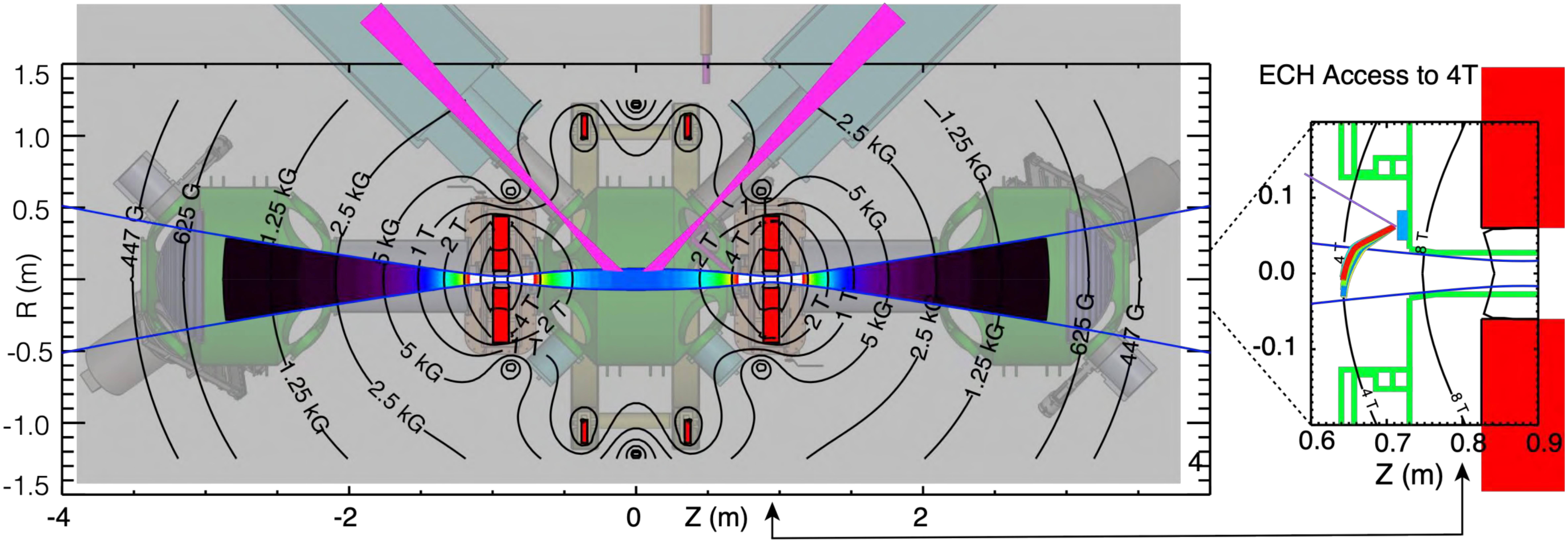
FIGURE 1. Schematics of the system. 1- position of plasma gun and vacuum pump, 2 - magnetic mirror, 3 - position of Langmuir probes, 4 - position of XUV photodiodes facing radially inwards. 5 - position of glass window for imaging measurements. 6 - Central magnetic coils, 7 - RMF antenna position.

Surface Line-Tying

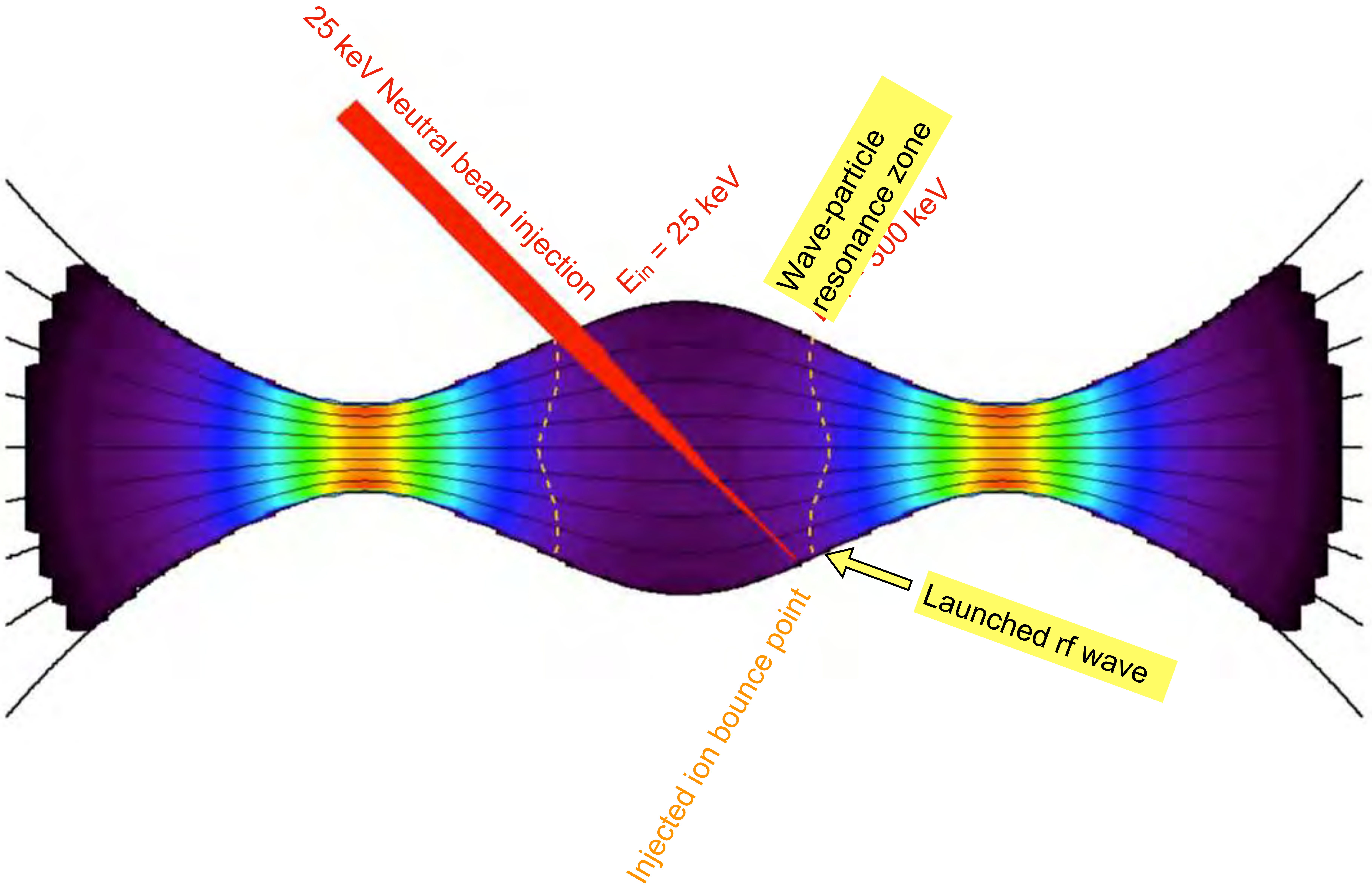
Fornaca, S., Kiwamoto, Y. & Rynn, N. Experimental Stabilization of Interchange Mode by Surface Line Tying. *Phys Rev Lett* **42**, 772–776 (1979).



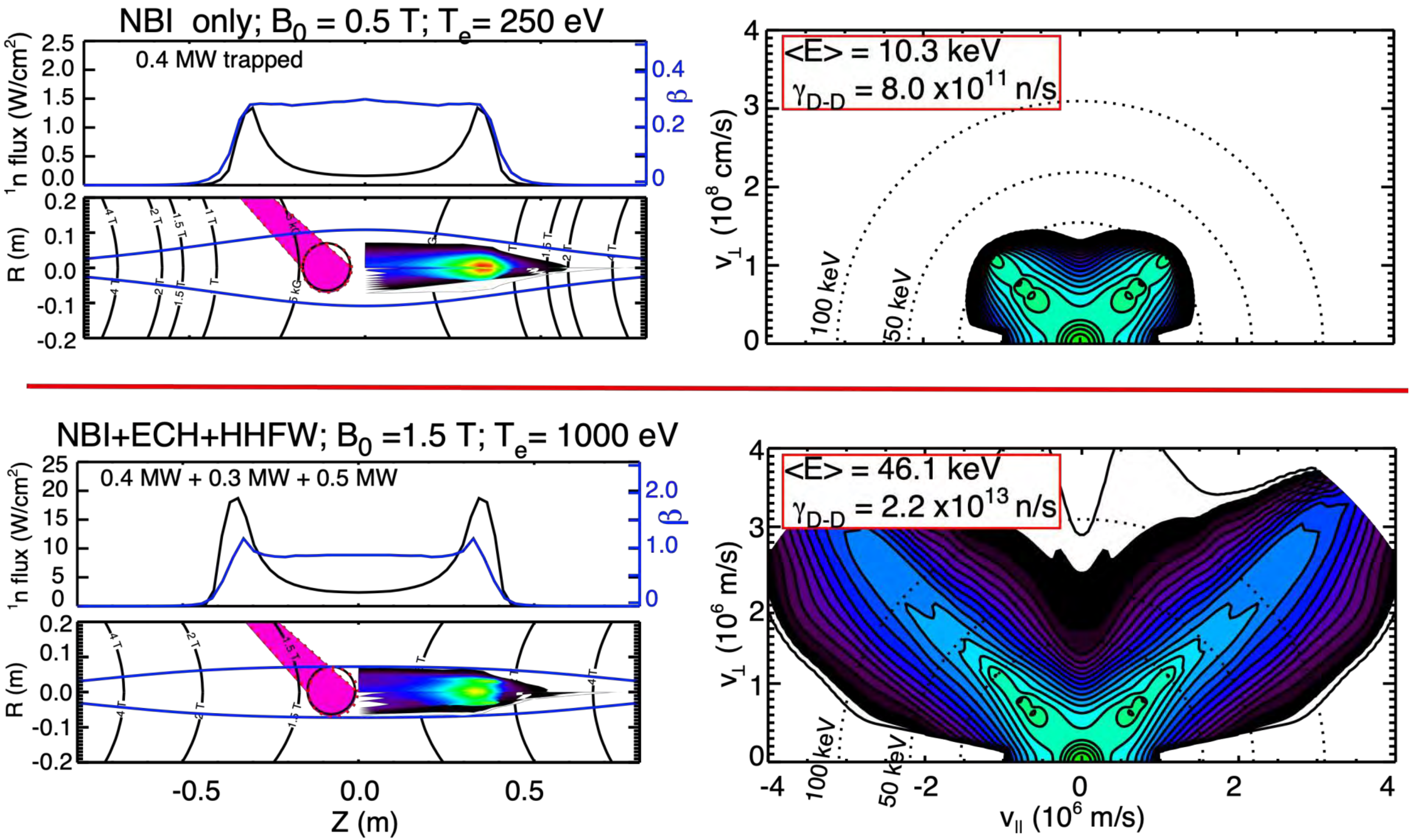
The heating cocktail for WHAM has been modeled using the CQL3D-genray suite of codes



Wave/ ion resonance leads to in-situ energization



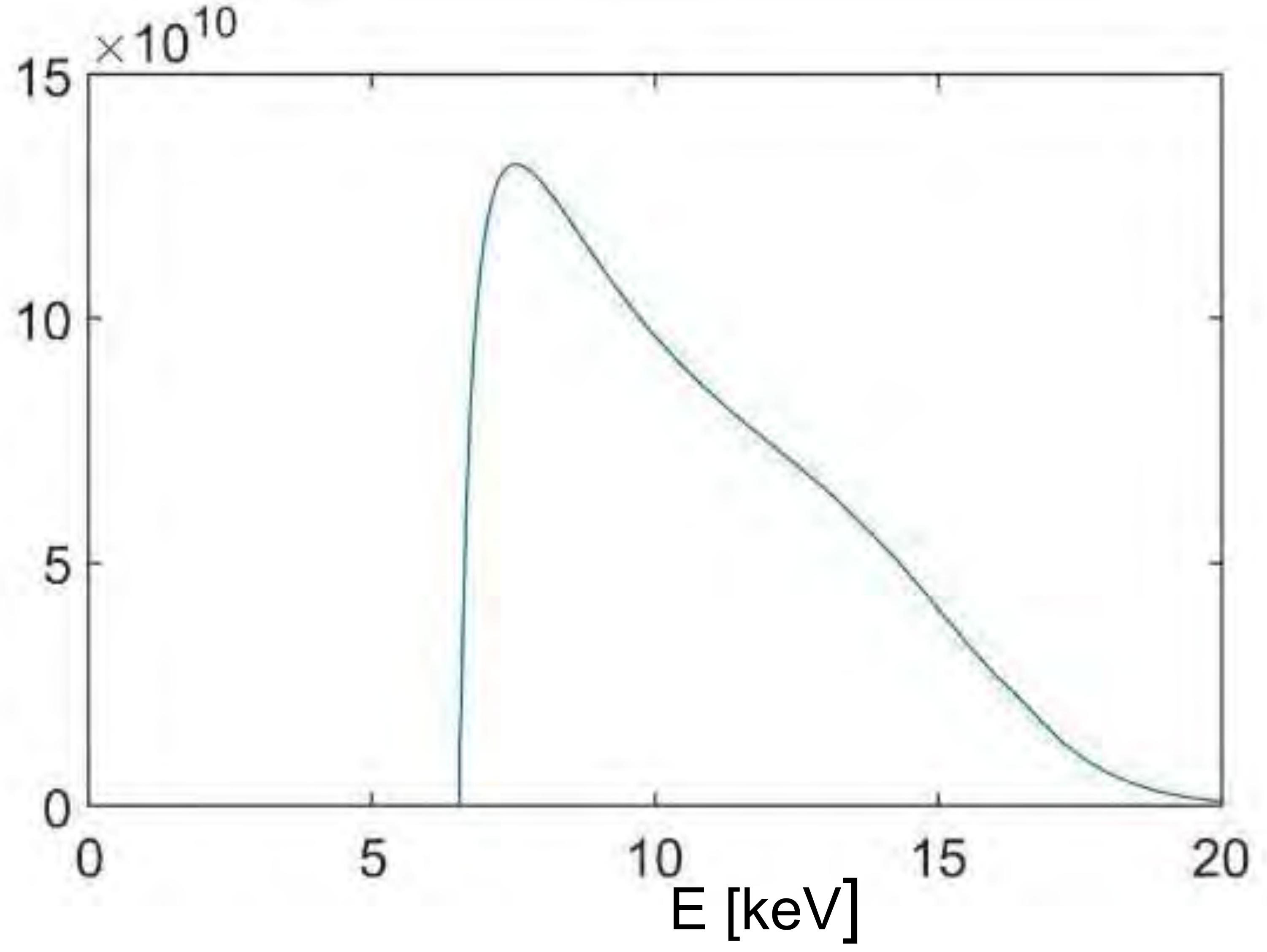
Fokker-Planck modeling of synergistic heating scheme shows in-situ ion acceleration; improved confinement



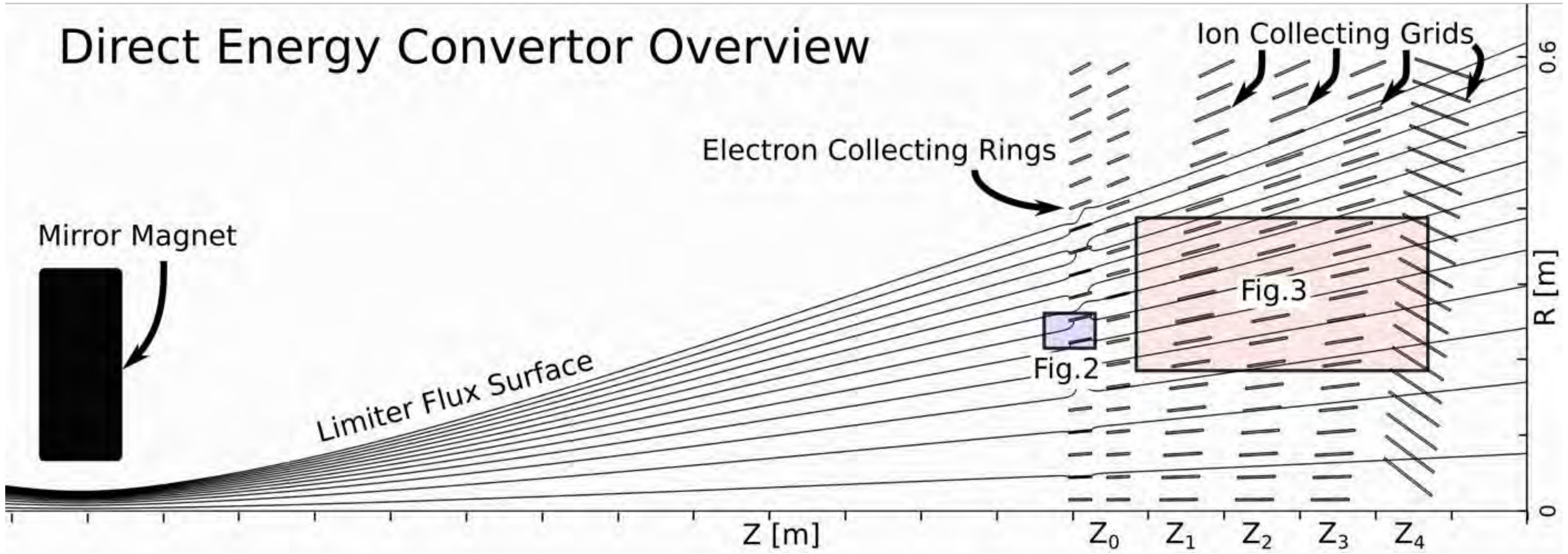
R. W. Harvey, Y. V. Petrov, and C. B. Forest, *“3D distributions resulting from neutral beam, ICRF and EC heating in an axisymmetric mirror,”* AIP Conference Proceedings 1771 , 040002 (2016).

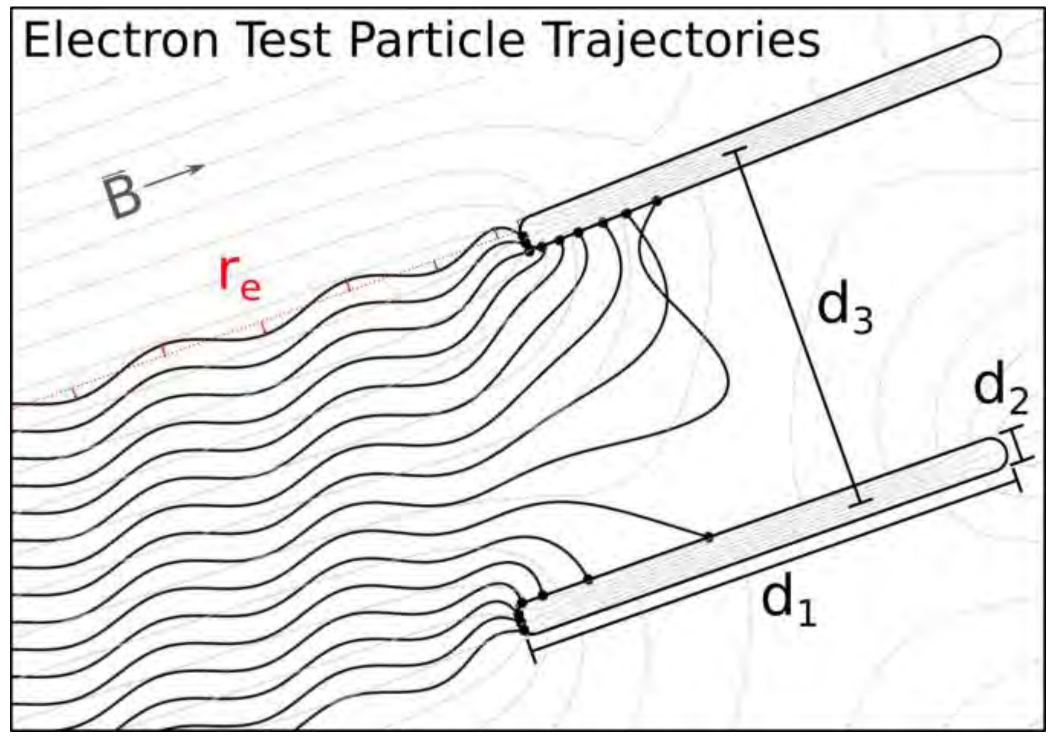
Use direct converter to recover ion exhaust energy

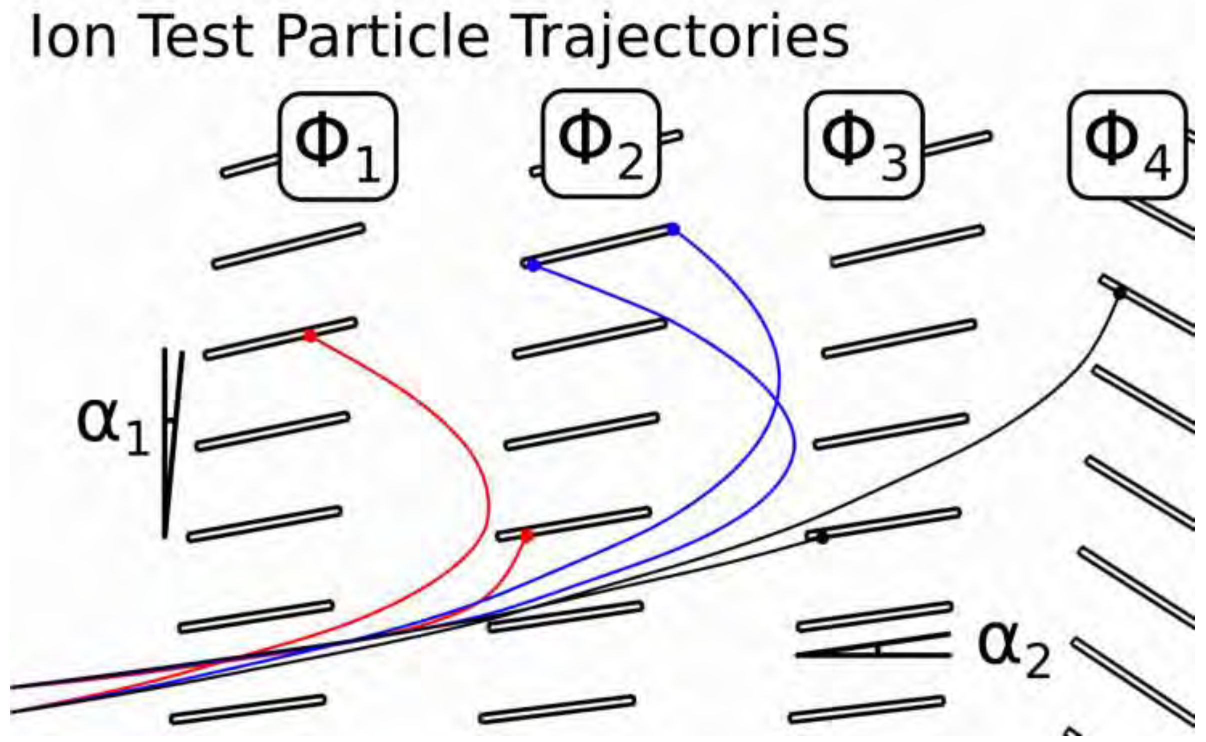
Lost ion energy spectrum



New design proposed using rings of magnetic iron to collect the electrons. Ion collected on biased electrodes.







Axisymmetric Tandem uses high pressure end plugs to confine thermal central cell plasma

Four species to consider:

1. High density plug
2. High Te plug electrons
3. Central cell electrons
4. Central cell thermal ions

Confined by:

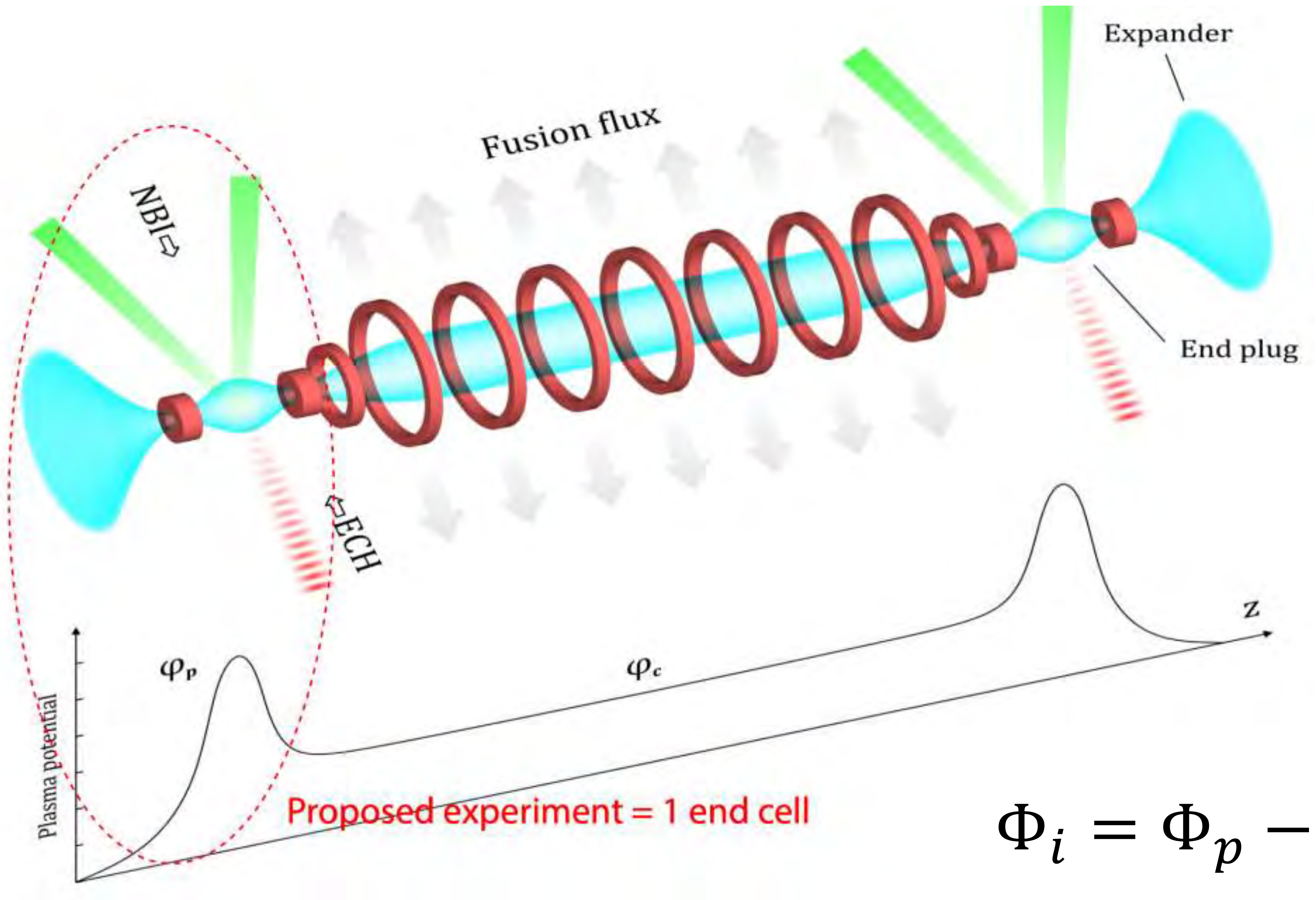
high energy ions

ambipolar potential associated with fast plug ions

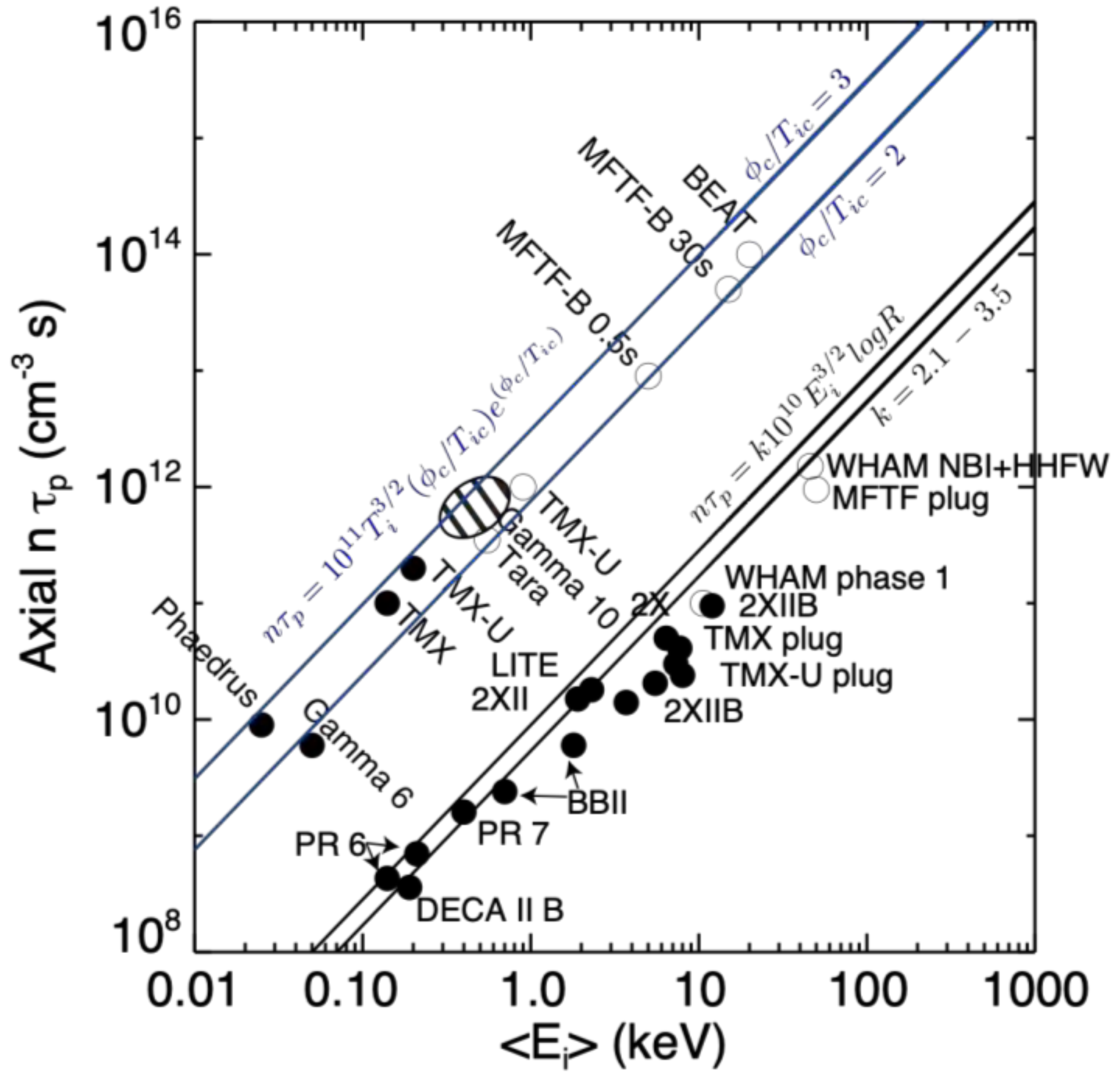
Confined by potential of expander

Pastukhov factor

Electrostatically confined by end plug potential $\tau_i \sim \tau_{ii} \ln R_M \Phi_i / T_{ic} e^{\Phi_i / T_{ic}}$



$$\Phi_i = \Phi_p - \Phi_c = T_{ep} ln(n_p / n_c)$$



T. K. Fowler, R. W. Moir, and T. C. Simonen, *A New Simpler Way to Obtain High Fusion Power Gain in Tandem Mirrors*, Nucl Fusion **57**, 056014 (2017).

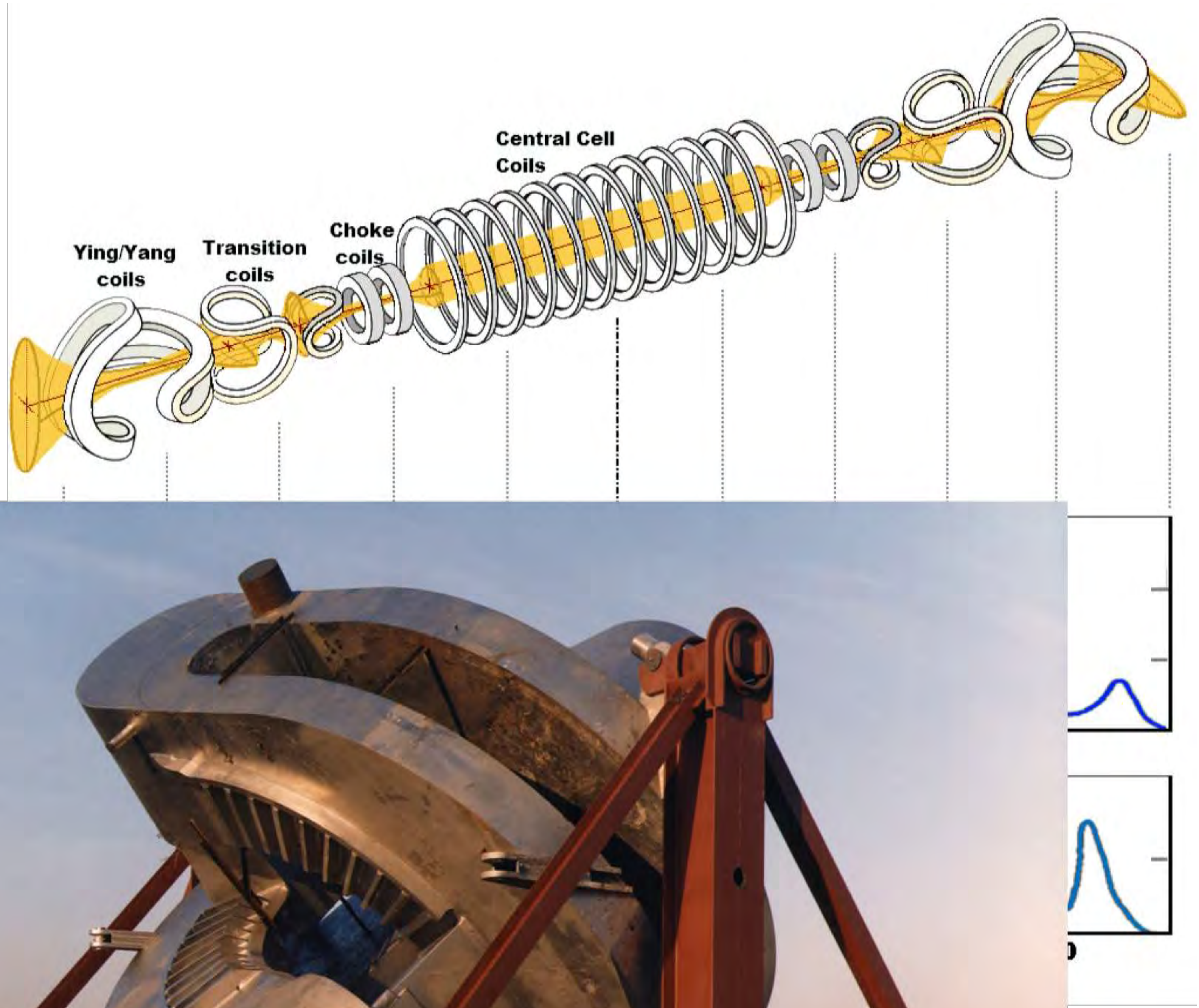
What's New (Summary)

1986: US cuts mirror research budget by ~95%

Perceived physics flaws
- required 3D coils
- mirror ratio limited by superconductors
- Complicated thermal barrier
- Low Te, poor electron confinement
- micro instabilities
- major technology gaps
  - superconducting magnets limited to < 12 T
  - >100 ghz cw gyrotrons nonexistant
  - MeV beams not available

Today:

Remarkable physics achievements
- Axisymmetric high β MHD stability
- High field enables simpler path to high Q (without thermal barrier)
- Axial electron thermal confinement from electric fields: Te~1 keV
- Major micro instabilities stabilized
- high mirror ratios now possible



MHD and Kinetic Instability

1. MHD
   - Vortex stabilization via cold edge plasma and by profile control of

$$E_r(r) \sim -5\frac{\partial}{\partial r}T_e(r)$$

   - feedback and conducting shells (at high β)
   - FLR (m>1)
   - divertors and short-fat mirrors
   - kinetic stabilization and/or modulated ECH (Kapitza Pendulum)
   - diamagnetic well self-stabilization

2. Alfvén Ion Cyclotron instability (apparently solved)
   - sloshing ions injected at 45 degrees, Landau damping by electrons with $k_{\|} \neq 0$

3. Drift Cyclotron Loss Cone Instability (to be demonstrated)
   - mitigate with large size and/or by filling ambipolar hole

4. Trapped Electron Modes (apparently solved)
- observed on TARA / mitigated on GAMMA-10)

  -Sheared flow created by ambipolar potential gradient control

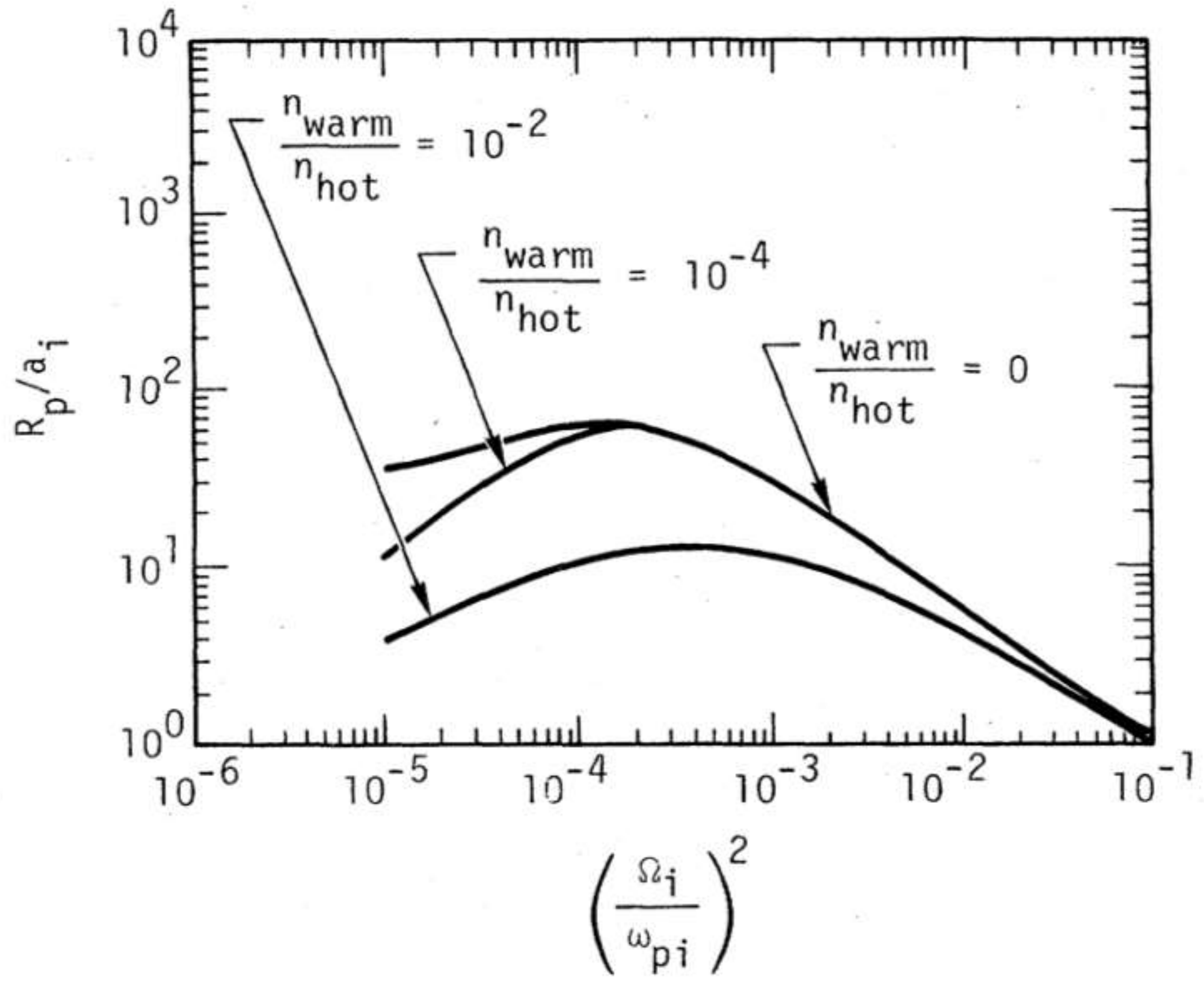


FIG. 7. Marginally stable radial scale lengths of drift-cyclotron loss-cone mode with addition of warm plasma; parameters are defined in the text.

That increasing the plasma radius does require less filling of the hole has already been demonstrated, in the range $R_p/\rho = 1.6$ to 6 [43]. Stability with an empty ambipolar hole is predicted for a plug radius $R_p > A_1$ (50ρ) and an adjustable parameter A_1. We obtain [42]:

$$R_p = A_1(50\rho) = 0.22A_1(E_o^{1/2}/B_p) \qquad (16a)$$

$(\omega_{pi}/\omega_{ci})^2$	10^2	10^3	10^4	10^5	
A_1	0.12	0.2	1.2	0.8	(16b)